Modélisation de l'élaboration du rendement et de la qualité de l'ananas Queen Victoria : application à la conception de systèmes de culture durables à la Réunion

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THÈSE

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Présentée par **Elodie DOREY**

Modélisation de l'élaboration du rendement et de la qualité de l'ananas 'Queen Victoria'- Application à la conception de systèmes de culture durables à la Réunion

Soutenue le 16 Décembre 2014 devant le jury composé de :

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Résumé

La culture de l'ananas s'est fortement développée à la Réunion et représente la première production fruitière de l'île en termes de valeur et de tonnage exporté. L'hétérogénéité des conditions climatiques de l'île ainsi que la diversité des pratiques culturales, notamment en ce qui concerne la fertilisation azotée et l'irrigation, mène à une forte variabilité des rendements, de la qualité gustative des fruits et d'utilisation des ressources naturelles du milieu. Le développement de systèmes de culture plus durables impose de repenser et d'optimiser l'assemblage des pratiques culturales, en prenant en compte les spécificités des différentes zones de production. Un modèle *ad-hoc*, SIMPIÑA a été développé afin de décrire la croissance et le développement de le la plante et la qualité gustative des fruits (teneur en sucres et en acides) en fonction du climat et des pratiques culturales (poids de rejets plantés, densité, date d'induction florale, fertilisation et irrigation). Ce modèle présente la particularité d'intégrer des modules mécanistes (croissance de la plante, teneur en sucre des fruits, bilans hydriques et azotés) et des modules statistiques pour la prévision de l'acidité des fruits à la récolte et la partie économique. Les pratiques culturales sont prises en compte au travers de règles de décision qu'il est ainsi possible d'évaluer. Une typologie des pratiques culturales a été élaborée sur 40 exploitations de l'île, en amont, afin de réduire le champ des possibles et permettre de proposer des systèmes de culture innovants, en optimisant les performances des systèmes tout en prenant en compte les principales contraintes des exploitations. SIMPIÑA a été utilisé pour identifier des combinaisons de pratiques culturales des systèmes qu'il conviendra de tester « au champ ». Cette approche intégrative a permis des avancées significatives au niveau de la modélisation de la culture de l'ananas et de la définition de systèmes de culture innovants.

Mots clés : système de culture ananas, modèle dynamique, qualité des fruits, évaluation multicritère, prototypage

Summary

Pineapple production is increasing on Réunion Island and represents the first fruit production, in terms of value and yield exported. The heterogeneity of climatic conditions on the island and the diversity of cultural practices, particularly with regard to nitrogen fertilization and irrigation, lead to a high variability in yield, gustatory quality of fruit and use of natural resources. The development of more sustainable cropping systems requires rethinking and optimizing the combination of agricultural practices, by taking into account the specificities of the different production areas. An *ad-hoc* model, SIMPIÑA was developed to describe the growth and development of pineapple plant and fruit quality (sugar and acid content) depending on climate and cultural practices (sucker weight at planting, planting density, date of flowering induction, fertilization and irrigation). This model has the particularity to integrate process-based model modules (plant growth, sugar content, water and nitrogen balance) and statistical modules (for predicting the acidity of fruit at harvest and the economic part). Cultural practices are taken into account through decision rules that may thus be assessed with the model. A typology of cultural practices was carried out based on interviews of 40 farmers all over Réunion Island and led to three farm's types with specific climatic and organizational constraints. SIMPIÑA was used to explore a wide range of combination of cultural practices, taking into account the constraints of each farm-type. We identified trends of cultural practices combinations which optimize the performances of the systems and that should be tested in the field. This integrative approach has led to significant advances in modeling pineapple production and in defining innovative cropping systems.

Keywords : Pineapple cropping system, dynamic model, fruit quality, multi-criteria evaluation, prototyping

Table des matières

Introduction

A l’heure où l’environnement se situe au cœur des débats politiques et publics, de nouveaux objectifs sont définis dans le secteur agricole afin de produire durablement, c'est-à-dire d’opter pour un mode de production productif, respectueux des ressources naturelles, des écosystèmes, de la santé humaine tout en étant acceptable par les populations qui doivent en vivre.

De par le monde, la culture de l’ananas est une des plus artificialisée, avec l’établissement de conditions de production via des apports d’intrants chimiques et des travaux du sol particulièrement poussés. Depuis une vingtaine d’années, sous l’impulsion de la demande à l’exportation, la culture de l’ananas s’est fortement développée à la Réunion et représente la 1ère production fruitière de l’île en termes de valeur et de tonnage exporté, avec une superficie dépassant désormais les 400 hectares pour une production d’environ 16 000 T (AROPFL, 2012). L’importance socio-économique de la filière ananas est majeure (plusieurs milliers d’emplois directs et indirects). La production est distribuée selon 3 voies de commercialisation : la vente locale, la transformation et l’exportation (qui représente environ 10 % de la production) et qui dépendent principalement du calibre du fruit et de la saison de récolte.

L’intensification de la culture par le recours aux intrants chimiques, impacte l’environnement (réduction de la biodiversité fonctionnelle par traitements et/ou désherbages systématiques, érosion des sols, …), les caractéristiques des fruits (hétérogénéité des stades de maturité, moindre résistance aux bioagresseurs, développement de la maladie des taches noires) et leurs qualités nutritionnelle et gustative. De plus, le contexte économique de ces dernières décennies a privilégié via cette intensification les critères de qualité ayant un fort impact sur la valeur marchande : calibre, aspect visuel et conservation des fruits. Parallèlement, les consommateurs qui sont très fortement incités à consommer des fruits et des légumes frais (Programme National Nutrition Santé), sont de plus en plus demandeurs de fruits sains, d’excellente qualité organoleptique et de haute valeur nutritionnelle, provenant de systèmes de production préservant l’environnement (même si cela ne se retrouve pas nécessairement dans leurs actes d’achats). Aujourd’hui, les préoccupations environnementales marquent de plus en plus le discours des producteurs de fruits réunionnais et la préservation du milieu naturel est une priorité compte tenu de la fragilité du milieu insulaire. C’est pourquoi la poursuite du développement de cette culture va ainsi l’amener à se confronter à 3 nouveaux enjeux majeurs liés au développement d’une agriculture durable :

- être en adéquation avec la demande de la société et des marchés pour une agriculture durable respectueuse de l’environnement
- garantir une production de qualité quelles que soient la saison et la zone de production
- être économiquement viable.

L’objectif général de la thèse consiste à développer et intégrer les connaissances relatives à l’effet des facteurs pédo-climatiques et des pratiques culturales sur l’élaboration du rendement et de la qualité de l’ananas à la Réunion pour *in fine* les combinaisons de pratiques culturales durables à mettre en œuvre dans chaque zones climatiques de l’ile.

La première partie de la thèse a été consacrée à la construction d’un outil de modélisation permettant de prédire le rendement, la qualité, les impacts environnementaux et le chiffre d’affaire du producteur d’une culture d’ananas à partir des variables climatiques et des pratiques culturales. La seconde partie de la thèse a consisté à utiliser l’outil de simulation dans le but de concevoir des systèmes de culture rentables, produisant des fruits de qualité tout en réduisant la fertilisation azotée, en prenant en compte les différentes contraintes des producteurs liées à leur zone de production et aux autres cultures présentes sur leur exploitation.

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Ce travail a donné lieu à 4 publications (1 publiée, 3 à soumettre) ainsi qu'à une présentation lors de congrès :

Publications scientifiques :

- Dorey,E., Fournier, P., Léchaudel, M. and Tixier, P., 2015. Validity of the pineapple crop model SIMPIÑA accross the climatic in Réunion Island, European Journal of Agronomy, 62, 1-12. *In press*

- Dorey,E., Fournier, P., Tixier, P.and Léchaudel, M., 2014. Linking an ecophysiological and a crop model to predict the effects of agro-climatic conditions on the sugar content of pineapples. (à soumettre à *European Journal of Agronomy*)
- Dorey,E., Fournier, P., Léchaudel, M. and Tixier, P., 2014. Effect of climatic conditions on pineapple acidity at harvest. (à soumettre à *Journal of Agricultural and Food Chemistry*)

- Dorey,E., Douraguia, E., Fournier, P., Michels, T., Rothé, M., Pissonier, S., Cambournac, T., and Tixier, P., 2014. Pineapple cropping system design with the SIMPIÑA modelling framework. (à soumettre à *Agricultural Systems*)

Communication orale lors de congrès :

- Dorey,E., Fournier, P., Léchaudel, M. and Tixier, P., 2014. SIMPIÑA, a comprehensive model to optimize yield, mineral resources, and fruit quality of pineapple. In ' XIIIth Congress of the European Society for Agronomy – Debrecen, Hungary 25-29 August 2014, Pépo, P. and Csajbók, J. editors. 510p. 209-210.

Chapitre I - Problématique générale

1. Les spécificités de l'ananas et sa culture

1.1. Biologie de l'ananas

L'ananas, *Ananas comosus* (L.) Merr est une monocotylédone herbacée appartenant à la famille des Bromeliacées. Cette plante se multiplie naturellement, après la production du fruit par reproduction végétative à partir du méristème terminal (donnant naissance à la couronne) ou à partir des bourgeons axillaires (qui forment des rejets latéraux sur la tige et le pédoncule). De la plantation à la floraison, la croissance du plant entier résulte de la croissance des feuilles, de la tige, et des racines (**Figure.I.1**). La part des feuilles représente 90 % de la masse fraiche du plant sans racine jusqu'à l'induction florale (Py, 1959). La phase floraison-récolte correspond à la mise en place d'un pédoncule, des organes floraux, de la couronne et au développement des rejets.

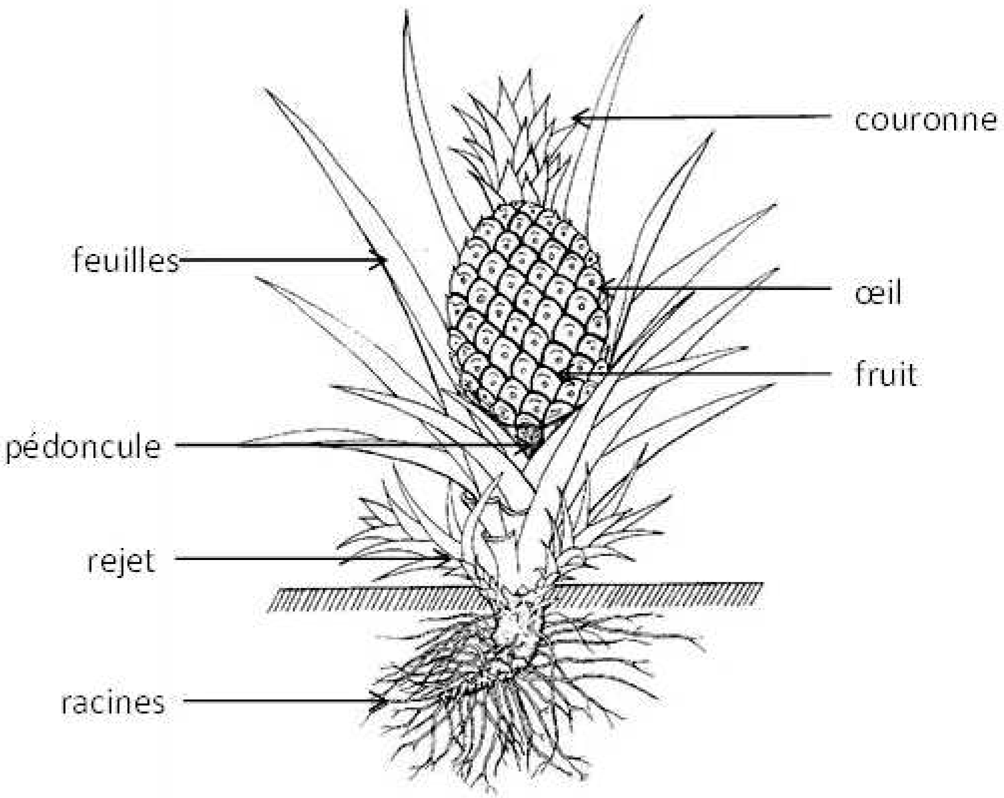

Figure I.1. L'ananas *Ananas comosus* (L.) Merr

L'ananas possède un métabolisme crassulacéen mis en évidence par Sideris and Krauss, (1948) et constitue un exemple unique parmi les plantes cultivées. La plante fixe le carbone en phase nocturne et l'acide malique accumulé n'est décarboxylé que dans la phase nocturne suivante. Les stomates s'ouvrent la nuit et se ferment le jour pour réduire les pertes d'eau lors de l'absorption du CO_2 atmosphérique. Comme la plupart de broméliacées, l'ananas se caractérise par une anatomie et une physiologie permettant l'économie de l'eau:

- l'organisation spatiale des feuilles, disposées en rosette et en forme de gouttière permet une récupération maximale des précipitations. L'eau peut être directement absorbée par les feuilles ainsi que les éléments dissouts (pulvérisations de fertilisants),
- en plus des racines du sol, des racines adventives aériennes situées à la base de la tige permettent d'absorber l'eau et les éléments minéraux ruisselant le long de la tige,
- la présence d'un tissu aquifère dans les feuilles (dont le volume varie avec les conditions hydriques, (Nightingale, 1936)) peut jouer également un rôle dans l'économie de l'eau.

Ces facteurs confèrent à l'ananas une bonne adaptation à la sécheresse en termes de survie. En cas de déficit hydrique, l'ananas voit sa consommation en eau ainsi que sa photosynthèse diminuer par rapport aux cycles en C3 et C4. Il n'est pourtant pas exclu que l'ananas utilise uniquement son métabolisme CAM, qui lui permet seulement de poursuivre sa photosynthèse à un rythme réduit, et aurait une meilleure productivité en évitant un métabolisme CAM trop intense.

La plupart des études menées sur la culture d'ananas ont porté sur 'Cayenne Lisse', cultivar le plus produit dans le monde jusqu'à une époque récente. Dans cette thèse nous nous intéresserons au cultivar 'Queen Victoria' qui représente l'essentiel de la production d'ananas sur l'île de la Réunion.

1.2 La culture de l'ananas

D'abord situés à Hawai, en 1960 Hawai produisait 70% de la consommation mondiale (Collins, 1960), les pôles de production de l'ananas se sont ensuite étendus à toutes les zones intertropicales chaudes et humides. La culture de l'ananas reste, quel que soit le type d'exploitation (culture paysanne au sein d'exploitations traditionnelles de petites surfaces aux grands blocs industriels de plusieurs milliers d'hectares), une culture exigeante en main d'œuvre et en intrants dans la plupart des cas.

1.2.1 Le contexte réunionnais

La Réunion est une île volcanique située dans l'Océan Indien, au Nord du tropique du Capricorne et à l'Est de Madagascar (21°10' S, 55°50' E). Par son relief très accentué, la Réunion possède un climat très contrasté, décrivant alors une large gamme de température, pluviométrie et de rayonnement solaire (**Figure I.2**).

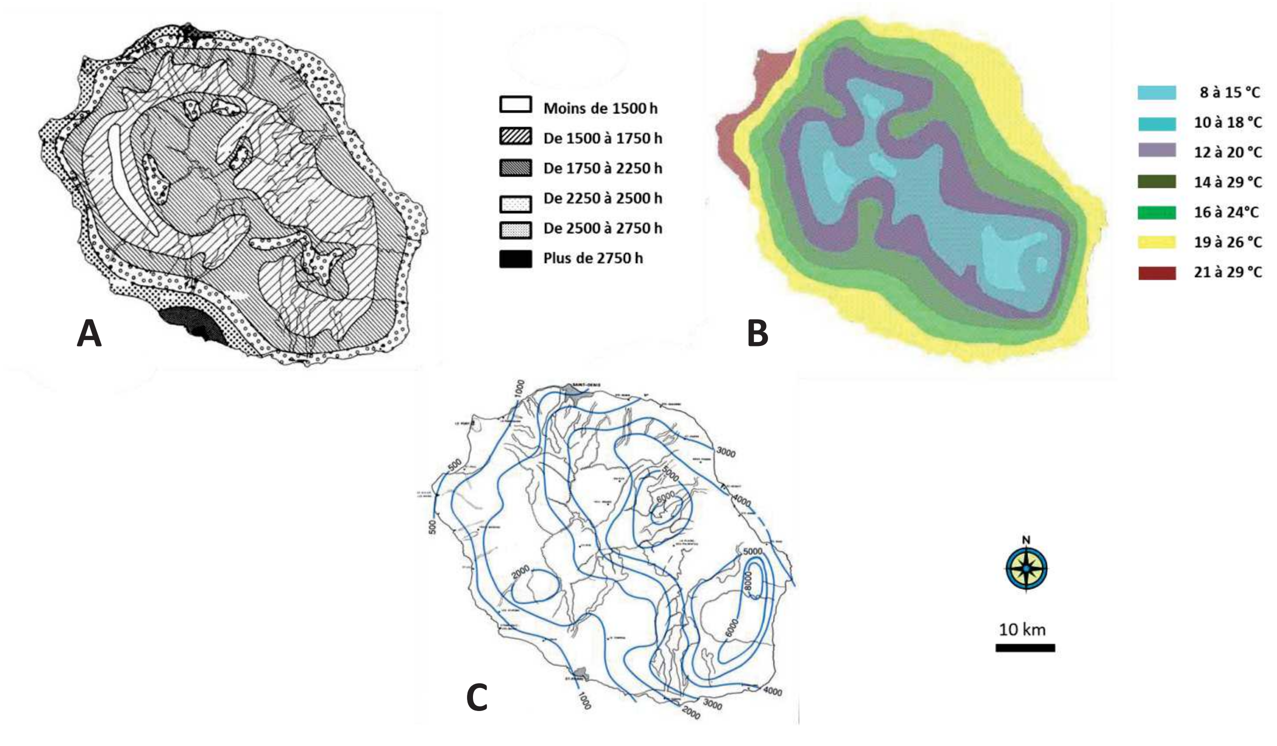

Figure I. 2. Cartes représentant (A) l'ensoleillement annuel moyen, (B) le gradient thermique annuel moyen, et (C) le gradient pluviométrique annuel moyen à la Réunion, adapté de Raunet (1991).

Depuis 1988, sous l'impulsion de la demande à l'exportation, l'ananas Victoria s'est fortement développé à la Réunion. L'hétérogénéité climatique implique des durées de cycle de production qui peuvent varier du simple au double avec un fonctionnement de la plante modifié et entraine donc des pratiques culturales variables (**Fig.I.3**).

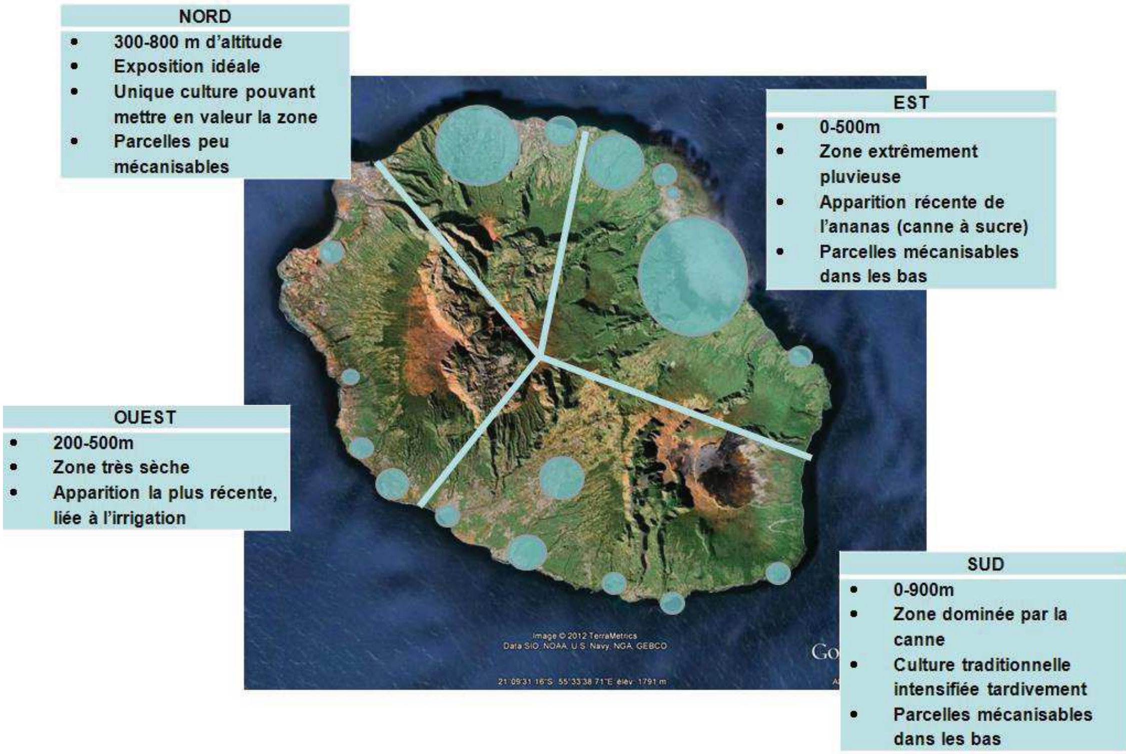

Figure I.3. Zones de production de l'ananas Victoria à la Réunion.

L'ananas est cultivé en monoculture, principalement de manière intensive, la plupart du temps sur paillage polyéthylène, avec des densités de plantation variables de 50 à 110 000 plants par hectare. La période de plantation s'étale toute l'année et implique des périodes de récolte toute l'année. On constate néanmoins deux pics de production en haute saison, à Pâques et Noël. Durant ces périodes, les exploitants sont assurés d'écouler leurs produits, même si les prix restent en général assez bas du fait d'une production de masse sur l'île, l'option de vente à l'export peut se montrer très intéressante en Décembre. La stratégie inverse, adoptée par certains producteurs, consiste à produire en hors saison (Mai à Octobre) dans le but d'obtenir des prix de vente plus élevés.

1.2.2 L'itinéraire technique

L'itinéraire technique détaillé ici est issu de l'itinéraire technique standard édité par le CIRAD et la Chambre de l'agriculture (Receuil des bonnes pratiques, Fournier, 2011).

La phase de préparation du sol est une phase capitale pour la culture de l'ananas car elle possède un système racinaire superficiel, descendant rarement en dessous de 35 cm et ses racines ne peuvent croitre que dans un milieu meuble, homogène, bien drainé et bien aéré. Tout changement dans la compacité du sol bloque le développement racinaire (semelle de labour, lit de gravillons…). Le pH du sol doit être compris entre 4,5 et 5,5 pour son bon développement. Après destruction du précédent cultural, les producteurs ont recours à un profond sous solage (60 à 80 cm, selon la nature du sol) pour obtenir un sol non compact et favoriser un drainage vertical. Puis, après un labourage profond (25- 30 cm) ils enfouissent la matière organique présente après l'avoir laissé sécher 2 à 3 semaines. Vient ensuite l'étape du billonnage, des billons d'environ 25cm de hauteur sont aménagés. C'est également à cette étape que le système d'irrigation est mis en place, dans les zones ayant un accès à l'eau. La fumure de fond, qui représente 20% des besoins totaux de la plante, soit 130 kg d'urée et 190 kg de sulfate de potasse ou encore 350 kg à l'hectare d'engrais complet de type 18-7-30 par exemple, alors incorporée au billon. Les billons sont ensuite recouverts d'un film polyéthylène noir, qui a pour effet positif de maintenir l'humidité du sol en saison sèche, de diminuer la compaction du sol, de réduire la croissance des adventices ou encore d'accroitre la température du sol et ainsi favoriser la croissance de la plante. L'emplacement en quinconce des plants est ensuite marqué ; selon la densité, chacun des billons comprendra 3 ou 4 lignes de plants.

Les producteurs s'assurent de la bonne qualité des rejets, avant leur plantation. Ils doivent être prélevés sur des plants sains. La majorité des producteurs de l'île produisent eux-mêmes leurs rejets et intègre à leur cycle une phase finale de production de rejets qui implique un bon entretien de la parcelle. Les rejets sont ensuite calibrés, souvent en 3 classes (petit, moyen, gros) allant en pratique de 150 à 400g avec une précision optimale de + ou – 25g., chaque classe de rejet étant plantée sur des billons différents ou des parcelles différentes. Les rejets sont ensuite plantés, avec une profondeur maximale de 10cm.

De la plantation à l'induction florale, une fumure d'entretien est appliquée. Les doses d'engrais sous doivent être fractionnées en fonction de la longueur du cycle prévue avec un rapport $K_2O/N \geq 1{,}5$. Aucun engrais ne sera appliqué après le traitement d'induction florale. Les besoins de la plante croissent avec son développement, 7 doses d'engrais constantes sont appliquées en diminuant l'intervalle entre les apports. Les cycles de production sont compris entre 11 et 20 mois, en fonction de l'altitude des parcelles, des dates de plantation ou encore du type de floraison (floraison induite par le producteur ou floraison naturelle en cas de diminution de la photopériode et de températures fraîches). Concernant l'irrigation, les besoins théoriques en eau de l'ananas sont d'environ 80 mm par mois sur sol nu. En période sèche et dans certaines zones de l'île, la culture intensive de l'ananas est inenvisageable sans irrigation. La majorité des producteurs ont recours au TIF (traitement d'induction florale), qu'ils effectuent à des moments différents au sein même d'une parcelle afin d'étaler la récolte et éviter un trop gros pic de travail ou à l'inverse de regrouper les récoltes à des dates prévues. Le TIF est effectué en vue d'obtenir des fruits du calibre souhaité à une époque déterminée. Le poids du plant au TIF, bon estimateur de la surface foliaire, est directement corrélé au poids du fruit à la récolte. Le nombre d'yeux du fruit étant fixé au moment de l'induction florale. Le rendement se décompose donc de la manière suivante : (i) nombre d'yeux et (ii) poids individuel d'un œil (remplissage atteint à la récolte). Le moment du TIF joue un rôle clé dans la croissance du fruit. Le poids moyen de la feuille D (feuille adulte qui vient de terminer sa croissance étroitement liée au poids du plant) pour obtenir des fruits de calibre export se situe entre 45 et 50g. La floraison est alors induite artificiellement à l'aide d'Ethrel concentré spécial ananas (Ethépon) appliqué en pulvérisation foliaire à raison de 30mL de solution par plant. Les inflorescences apparaissent 4 à 8 semaines après le TIF, en fonction de l'altitude de la plantation et de la saison.

La maturité des fruits, dépend de critères chimiques (sucres, acidité, vitamine C) et physiques (fermeté de la chair, translucidité, couleur externe du fruit). Une forte corrélation existe à la Réunion entre la coloration externe naturelle du fruit du 'Queen Victoria' et sa maturité. Les fruits sont donc récoltés lorsque la coloration jaune dépasse la moitié de la hauteur du fruit.

Bien qu'un itinéraire technique standard ait été édité, préconisant une fertilisation de 300 unités d'azote et 450 unités de potassium, répartis en 7 apports au cours du cycle végétatif, les pratiques réelles des producteurs sont en fait beaucoup plus larges. Les doses d'azote varient de 0 à plus de 500 unités et le nombre d'apports varie préférentiellement en fonction de la durée du cycle en appliquant une dose d'engrais tous les mois jusqu'au (TIF). Les grandes étapes de l'itinéraire technique de la culture de l'ananas sont décrites Figure **I. 4.**

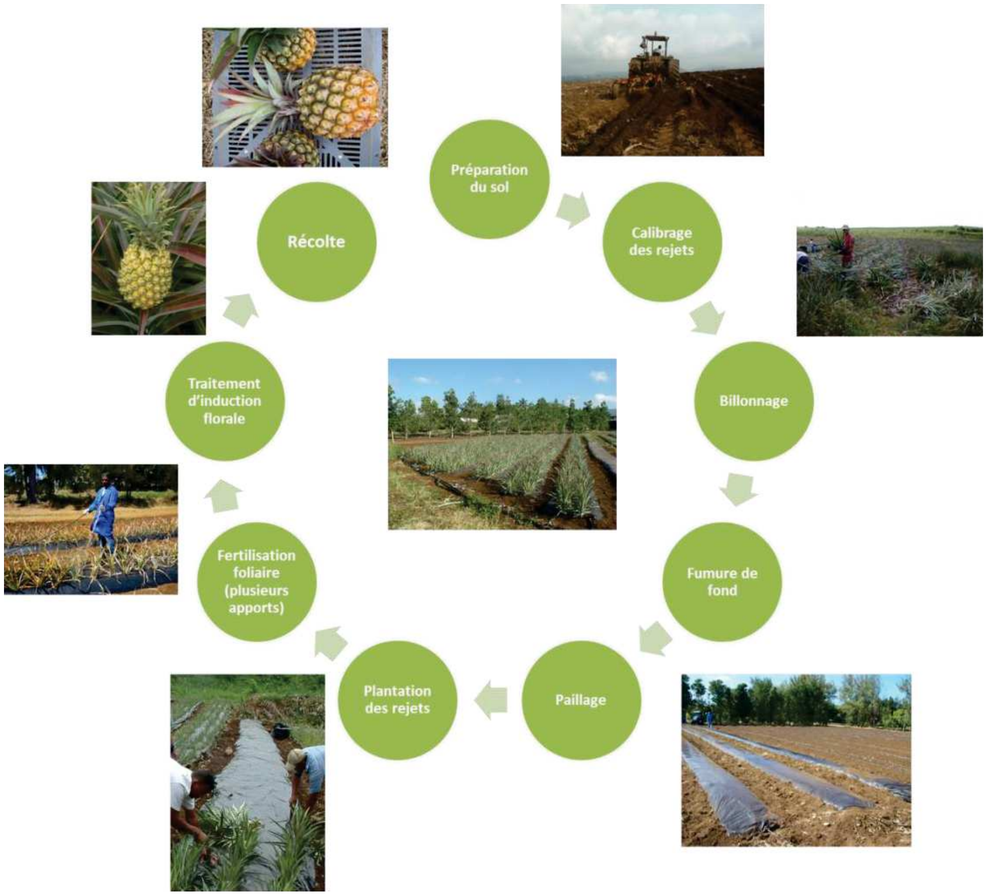

Figure I.4. Représentation des principales étapes de l'itinéraire technique pour la culture de l'ananas à la Réunion. Photos : P. Fournier, M. Darnaudery

Même si l'objectif de l'itinéraire technique est généralement de rechercher une production la plus homogène possible, on observe une très grande variabilité en termes de rendement et de qualité en fonction des zones de production et des pratiques culturales. Il est donc essentiel d'adapter l'itinéraire technique selon la saison et la zone de production. Pour ce faire, il apparait nécessaire de préciser les connaissances sur la croissance et le développement de l'ananas, au sein d'un modèle *ad-hoc* qui simulera la croissance et le développement de la plante mais aussi la qualité gustative des fruits, représentés par les teneurs en sucres et en acides, et d'analyser la diversité des pratiques culturales sur l'île sur la base d'une typologie. L'objectif étant de chercher à comprendre les déterminants des choix techniques en fonction des stratégies des producteurs et des conditions pédoclimatiques dans lesquelles ils sont amenés à exercer leurs activités. Les marges de manœuvre dont ils disposent pour maximiser les performances de leur système seront analysées afin concevoir des systèmes de cultures innovants et durables.

2. La conception des systèmes de culture

Un système de culture peut être défini comme « *l'ensemble des modalités techniques mises en œuvre sur des parcelles traitées de manière identique ; chaque système de culture se caractérise par la nature des cultures et leur ordre de succession, et par les itinéraires techniques appliqués à chacune de ces cultures* » (Sebillotte, 1990). Il constitue donc un système complexe qui, au sein d'une zone géographique donnée évolue au cours du temps, avec des contraintes associées.

Pendant longtemps, l'expérimentation au champ a été le seul support des agronomes pour concevoir et évaluer des systèmes de cultures innovants (Lançon *et al.*, 2007). Ces méthodes de conception se sont avérées efficaces pour tester différents facteurs en vue d'améliorer principalement le rendement, mais elles se montrent insuffisantes, longues et coûteuses dans un climat variable et des sols diversifiés impliquant des nombreuses combinaisons techniques. De plus, elles n'intègrent que rarement la qualité du fruit produit. Des démarches de conception à base de modèles agronomiques (Doré *et al.*, 2008) ou de prototypage (Lançon *et al.*, 2007) permettent d'élargir le champ des solutions explorées.

Loyce and Wery (2006), propose une démarche en 4 étapes pour concevoir des systèmes de culture : (1) Définition du cadre de contraintes et d'objectifs pour le système à concevoir (2) Génération des systèmes de cultures potentiels, étape de conception au sens propre, (3) Evaluation des performances des systèmes de culture potentiels, (4) Identification des systèmes candidats pour diffusion. Les phases de conception et d'évaluation peuvent faire l'objet d'étapes intermédiaires définies par Bergez *et al.* (2010) afin d'améliorer la démarche pas à pas (**Fig. I.5**).

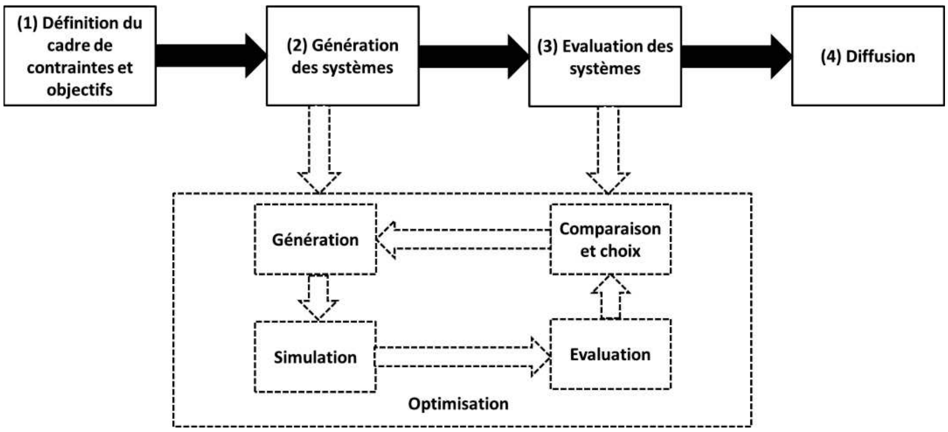

Figure I.5. Représentation des différentes phases de la démarche de conception de systèmes de culture (1 à 4) d'après Loyce & Wery, (2006), et représentation des différentes étapes intermédiaires d'après Bergez et al., (2010) .

2.1 Quelles méthodes pour concevoir?

La démarche générale pour la conception de systèmes de culture définie par Loyce and Wery (2006) implique la mobilisation d'outils spécifiques de différentes natures à chaque étape du processus de conception. Trois méthodes ont été définies pour générer des systèmes de culture potentiels le diagnostic agronomique, le prototypage à dire d'expert et la modélisation.

Le diagnostic agronomique permet de relier des actes techniques aux performances du système en identifiant les facteurs limitants et ainsi les leviers d'action mobilisables pour l'amélioration des performances. La modélisation, utilisée *a posteriori* pour le calcul de différents indicateurs ou l'expérimentation, avec ses limites exploratoires évoquées ci-dessus, seront utilisées dans cette première méthode de conception.

Les deux méthodes de conception suivantes, le prototypage à dires d'experts (Lançon *et al.*, 2008; Vereijken, 1997) et la conception assistée par modèles (Bergez *et al.*, 2010), sont des approches de conception qualifiées « *de novo* », qui vise à proposer des prototypes innovants et construits pour répondre à des objectifs, par opposition à la conception « pas à pas » utilisée pour une amélioration progressive de l'existant en ajoutant de nouveaux objectifs. La conception *de novo* est une démarche itérative et implique une alternance entre les phases de (2) génération et (3) évaluation.

La méthode de prototypage consiste à définir un prototype théorique à dires d'experts une fois le cadre de contraintes biophysiques et techniques défini. Il s'agit ici de valoriser les savoir des experts (plutôt génériques) et les avoirs des utilisateurs (plutôt locaux). Le prototypage s'effectue en deux étapes, une étape d'exploration virtuelle de solutions innovantes à dires d'experts et une étape participative de mise au point, d'expérimentation et d'évaluation au champ. Des critères et indicateurs d'évaluation sont définis afin de mesurer les performances du système. Cette étape d'évaluation peut s'effectuer à l'aide de modèles. Suite à la phase d'évaluation, les règles de décision stratégiques et tactiques pilotant le système sont alors optimisées et réajustées en testant des variables alternatives de contrôle de ces règles de décisions expérimentalement, puis réévaluées. L'implication des acteurs dès les premières de la méthode peut s'avérer très efficace pour améliorer et adopter les prototypes comme le montre l'étude de Hossard *et al.*(2013) sur le phoma du colza, maladie responsable d'importantes pertes de productivité du colza en Europe. Les acteurs de la filière ont été consulté avant la conception de scénarios de pratiques, afin d'avoir une vision commune du fonctionnement et de l'impact de la maladie sur les cultures de colza, pendant la phase de conception, et durant la phase d'évaluation.

La troisième méthode, i.e. conception assistée par modèle, fera l'objet du chapitre suivant puisqu'elle correspond à la méthode de conception choisie pour aborder les questions de recherche de la thèse.

2.2 L'apport de la modélisation pour la conception de systèmes de culture durables

L'évaluation et la conception de nouveaux d'itinéraires techniques ou de systèmes de cultures par simulation s'inscrit dans une démarche complémentaire à l'expérimentation (Bergez *et al.*, 2010; Loyce and Wery, 2006; Rossing *et al.*, 1997). La simulation, offre la possibilité d'explorer une gamme plus vaste de situations dans un intervalle de temps restreint (Semenov *et al.*, 2009) et permet de simuler l'effet des interactions entre le climat, le type de sol et les techniques culturales sur le fonctionnement de la culture. Elle permet, en fonction du modèle de culture utilisé, d'avoir accès à une diversité d'indicateurs difficilement accessibles par expérimentation. Les modèles de culture sont majoritairement constitués d'un ensemble d'équations mathématiques traduisant les processus de fonctionnement du système sol – plante (approche mécaniste) mais peuvent intégrer des relations empiriques entre les variables caractérisant les processus.

La conception assistée par modèle se base ainsi sur le développement de modèles associant un modèle biophysique, qui représente le fonctionnement de la plante cultivée sous l'influence des conditions climatiques et des techniques culturales (Doré *et al.*, 2006), couplé à un modèle décisionnel, qui représente les stratégies des agriculteurs dans la mise en œuvre de leurs pratiques (Keating *et al.*, 2003).

Les modèles peuvent être utilisés à plusieurs étapes de la conception de systèmes de culture : de la phase de conception au sens stricte, qui génère de nouveaux systèmes, comme le modèle BETHA (Loyce *et al.*, 2002), DECID'Herb (Munier-Jolain *et al.*, 2005) en grande culture ou le modèle pêcher vs puceron (Grechi *et al.*, 2012) ou SIMBA (Tixier *et al.*, 2008) en arboriculture et production fruitière, en passant par les phases d'évaluation et d'extrapolation des résultats dans d'autres situations pédoclimatiques jusqu'à la phase de diffusion, si il s'agit d'un modèle d'aide à la décision. Les modèles peuvent également intervenir dans la phase plus aval de la conception, pour évaluer par exemple le potentiel d'adoption des innovations. L'étude de Blazy *et al.* (2009) montre que les agriculteurs se trouvent dans des conditions d'exploitations (biophysiques et socioéconomiques) très différentes qui impliquent des intérêts et des marges de manœuvres variables. En couplant le modèle de système de culture bananiers SIMBA (Tixier *et al.*, 2008) et le modèle d'exploitation BANAD (Blazy *et al.*, 2010), les processus d'adoption et de conduite de l'exploitation (assolement, conduite technique et gestion de la main d'œuvre) ont été simulés. Il est alors possible d'analyser les déterminants de l'adoption de certaines innovations comme les rotations par exemple.

La modélisation présente ainsi de nombreux avantages puisqu'elle intègre les connaissances issues de différentes disciplines, décrit les processus impliqués dans le système, fournit des indicateurs difficilement mesurables lors d'expérimentations et teste les systèmes dans une large gamme de conditions pédo-climatiques et de pratiques difficilement réalisables en champs dans un délai relativement court (Ahuja *et al.*, 2014). Néanmoins, la conception de système de culture assistée par modèle montre certaines limites, principalement basées sur le domaine de validité ou leur degré de complexité. Le domaine de validité des modèles dépend partiellement de la qualité et de la quantité des données utilisées (et de leur gamme) pour la paramétrisation et l'évaluation du modèle et du niveau de description des processus (Affholder *et al.*, 2012). De plus, la complexité n'assure en aucun cas une extension du domaine de validité du modèle (Boote *et al.*, 1996; Sinclair and Seligman, 1996). La manière dont les processus sont pris en compte au sein du modèle dépend principalement des objectifs de modélisation (Affholder *et al.*, 2012). Récemment, on voit apparaitre des études sur l'utilisation d'approches de réduction de modèles afin d'évaluer l'adéquation de la structure du modèle étudié et de sélectionner le niveau de complexité le plus approprié (Affholder *et al.*, 2003; Cox *et al.*, 2006; Crout *et al.*, 2009; Kimmins *et al.*, 2008). Ces études permettent d'évaluer si la prise en compte de certains processus est nécessaire au bon fonctionnement du modèle pour simuler les variables désirées afin de répondre à la question posée. Le cas échéant, ces processus peuvent être supprimés pour une plus grande simplicité du modèle. La suppression des processus de stress du modèle conduit à de larges erreurs de simulation du poids de fruit par rapport au modèle le plus complexe. Les processus inclus dans SIMPIÑA semblent donc nécessaire au bon fonctionnement du modèle pour simuler le rendement de la plante dans la gamme de conditions testées.

Un autre point important à mentionner dans la conception de système assistée par modèles est le degré de participation des acteurs (agriculteurs ou conseillers) dans le processus de conception. La plupart des études de modélisation ne font pas intervenir les acteurs dans les processus de conception. D'autres montrent des degrés différents de participation des acteurs, où ceux-ci sont impliqués dans la définition des objectifs du système (Stoorvogel et al., 2004), dans l'acquisition de données sur leurs exploitations (Castelan-Ortega et al., 2003), dans la collaboration avec la recherche pour la construction et l'utilisation du modèle afin de répondre à un objectif précis (Vayssières et al., 2007) ou dans l'évaluation du système (Defoer et al., 1998). Dans le but de concevoir des systèmes innovants, aboutissant à leur diffusion auprès des acteurs, il est important de se positionner avant la démarche de conception sur le degré d'implication des acteurs en fonction de l'objectif ciblé.

Aujourd'hui, la conception de systèmes innovants doit répondre à de multiples défis, à la fois environnementaux (limitation du transfert des pesticides et des nitrates, réduction des émissions de gaz à effet de serre, préservation de la biodiversité, …) et de production alimentaire (sécurisation et augmentation de la production, amélioration de la qualité des produits, adaptation à l'économie, …), dans une optique de durabilité (Ahuja et al., 2007). De nombreux modèles prennent en compte la plupart de ces critères, mais l'élaboration de la qualité des produits reste souvent absente, malgré l'importance de ce critère dans la définition de la durabilité des systèmes. La prise en compte de la qualité sera donc abordée dans le chapitre suivant.

2.3 La prise en compte de la qualité des produits dans les modèles de culture

2.3 La prise en compte de la qualité des produits dans les modèles de culture

L'amélioration de la qualité des produits devient une préoccupation de santé publique, économique et scientifique c'est pourquoi la qualité des fruits prend une place de plus en plus importance au sein de la production fruitière. Les facteurs environnementaux, tels que la lumière, la température, la disponibilité en carbone et en eau, influencent les processus physiologiques impliqués dans l'élaboration du fruit. Auparavant, la qualité était majoritairement représentée par le calibre et la couleur des fruits, mais est désormais envisagée par un ensemble d'attributs gustatifs (saveur sucrée, acidité) et nutritionnels (antioxydants, vitamine C). Néanmoins, la qualité gustative des fruits est extrêmement variable et difficile à gérer par les producteurs (Basile et al., 2007; Genard and Bruchou, 1992; Taylor et al., 2007) puisqu'elle dépend à la fois du climat et des pratiques culturales.

Ces facteurs vont influencés l'accumulation des sucres et des acides, composés principaux de la qualité gustative des fruits.

L'approche expérimentale classique ne permettant pas d'avoir une image suffisamment intégrée du fonctionnement du fruit, des modèles de croissance de fruit ont donc été développés. De nombreux modèles en arboriculture simulent la répartition du carbone au sein d'un arbre en fonction du stress hydrique par exemple mais ne traitent pas de la qualité des fruits (Allen et al., 2005 ; Costes et al., 2008). La prise en compte de la qualité s'effectue à l'aide de modèles écophysiologiques, dans lesquels sont élaborés des processus complexes comme la respiration, la photosynthèse, l'assimilation et la répartition des assimilats par la plante. Ces modèles simulent comment l'environnement et le métabolisme des plantes affectent la croissance du fruit et sa qualité. En 2005, Lescourret et Génard ont proposé un modèle de fruit virtuel simulant les transformations de la qualité des fruits au cours de leur croissance en fonction du climat et sous l'influence de certaines techniques. Récemment, Lescourret et al. (2011) ont également développé le modèle Qualitree qui simule cette fois la croissance végétative de la plante et le développement du fruit, en fonction des processus physiologiques et des pratiques culturales du système de culture. Les connaissances des principaux processus du fonctionnement des plantes sont intégrés progressivement à des sous module de croissance de fruits et d'élaboration de la qualité, qui interagissent avec le climat et les pratiques culturales. Face aux nouvelles préoccupations en termes de durabilité des systèmes, les changements techniques dans la conduite d'une culture imposent d'appréhender dans sa globalité ses effets sur le système de culture. En effet, les techniques développées pour améliorer la qualité des fruits, en réduisant l'utilisation des pesticides ou des intrants chimiques par exemple, induisent souvent une réduction de calibre, l'apparition de défauts visuels ou un surcout économique, qui diminuent le potentiel d'adoption des innovations techniques par les producteurs. Lier les processus physiologiques impliqués dans l'élaboration de la qualité à un modèle de culture pour comprendre comment la qualité est affectée par le climat et les pratiques culturales s'avère très utile. Cela permet d' explorer quantitativement l'effet de combinaisons de techniques en fonction de conditions climatiques variées en vue d'évaluer les systèmes simulés d'un point agronomique, environnemental et économique mais aussi avec des critères de qualité des produits, qui auront un impact non négligeable sur la commercialisation et la valorisation des produits. L'étude de Loyce (2007) sur la production de blé éthanol est un très bon exemple d'évaluation muticritère d'itinéraires techniques Le modèle développé simule à la fois le rendement, la quantité d'azote minéral restant dans le sol à la récolte ainsi que la teneur en protéines de grains pour répondre à un cahier des charges définis. Chaque itinéraire technique est donc évalué aux yeux de l'ensemble des critères.

2.4. Les outils de simulation associés à la culture de l'ananas

Les travaux de Malezieux (1988) se sont concentrés sur les règles de fonctionnement du peuplement végétal qui régissent la croissance de la plante et le rendement sur la variété 'Cayenne Lisse' en Côte d'Ivoire. Il a démontré l'importance de la biomasse aérienne à l'induction florale sur la fixation des composantes du rendement, l'influence de la compétition pour la lumière et l'azote dans la fixation de cette biomasse mais également l'importance des conditions climatiques après l'induction florale sur l'élaboration du rendement final. Il manque néanmoins des travaux sur la dynamique de l'azote et du carbone dans la plante en vue d'une meilleure gestion de ces éléments pour compléter son travail.

Quelques années plus tard, à Hawai, Zhang (1992) constate qu'il est toujours difficile de prédire le rendement et la date de récolte des plantations d'ananas dans des environnements contrastés. D'après le modèle CERES Maize, il construit le modèle ALOHA (Assessments of Local Options for Hawai Agriculture) qui simule les effets de la densité et de la date de plantation sur le poids du plant à l'induction florale et le rendement. Mais ce modèle reste valide uniquement dans les conditions de production Hawaïenne, en conditions non-limitantes et aucune donnée sur la qualité des fruits n'est fournie.

En 2010, AnaGmax, logiciel d'aide à la gestion des plantations d'ananas a été élaboré au CIRAD (Fournier et al., 2012). A partir des températures enregistrées et de certaines caractéristiques de la parcelle (localisation géographique, variété, matériel végétal, date de plantation), AnaGmax calcule les dates potentielles des phases clés du cycle de production (date d'induction florale, de floraison, de récolte). Il est donc axé sur la phénologie de la plante. En se basant sur l'itinéraire technique de référence, AnaGmax l'adapte au cycle prévisionnel de la parcelle. Ce logiciel permet de piloter la production en aval : en indiquant une période de production souhaitée et un tonnage dans une zone donnée, le logiciel indique les surfaces à planter et les dates de plantations souhaitables. Les producteurs ont maintenant la possibilité de produire selon des normes de planification plus régulières afin d'appréhender au mieux la date de leur récolte. Ce logiciel de prédiction reste pourtant incomplet : (i) il ne prend pas en compte le lien entre l'élaboration du rendement et de la qualité et les pratiques culturales associées, (ii) il est basé sur un itinéraire technique de référence, et (iii) il ne prend pas en compte les règles de décisions des agriculteurs.

Il est donc nécessaire de construire un nouvel outil, qui prend en compte l'effet des stress de hydrique et azoté de la culture, pour permettre aux producteurs de mieux gérer le cycle de la plante via des itinéraires techniques innovants dans les conditions pédoclimatiques variées à la Réunion en tenant compte de leurs contraintes au sein de leur exploitation.

3. Problématique scientifique et démarche générale

L'objectif général de la thèse est de rechercher, pour les différentes conditions de production d'ananas 'Victoria' à la Réunion, quelles pratiques culturales mettre en œuvre afin de prendre en compte les trois piliers de la durabilité (production de qualité, viabilité économique, respect de l'environnement) dans les différentes zones de production de l'île.

Pour cela un outil permettant de simuler la croissance et le développement de la plante, la qualité gustative des fruits (teneur en sucres et en acides), le lessivage de l'azote et le revenu du producteur à la commercialisation sera développé en fonction du climat et des pratiques culturales (poids de rejets plantés, densité de plantation, date d'induction florale, fertilisation et irrigation). La démarche proposée se structure autour de trois questions de recherche traitant des deux grandes parties de construction du modèle (élaboration du rendement et élaboration de la qualité) puis de l'utilisation du modèle pour l'optimisation des pratiques dans des contextes de production variés :

- Q1. Comment intégrer dans un modèle le fonctionnement biophysique et l'élaboration du rendement de l'ananas 'Queen Victoria' ?
- Q2. Comment prédire les composantes de la qualité (teneur en sucres et en acides) de l'ananas 'Victoria' ?
- Q3. Quelles règles de décision permettent d'optimiser les performances (agronomiques, de qualité des fruits, environnementales et économiques) des systèmes de culture ananas dans les différentes conditions pédoclimatiques et d'exploitations de la Réunion ?

Les trois questions de recherche présentées ici seront traitées au sein des trois chapitres suivants (chacun étant composé d'un ou deux articles scientifiques).

La croissance et le développement de la plante en fonction du climat et des pratiques culturales seront traités dans le chapitre II. Ce chapitre présente la construction, la calibration et la validation de la partie 'soil-plante' du modèle SIMPIÑA. Cette partie du modèle intègre trois modules mécanistes : un module de croissance de la plante, lié à des modules sols qui simulent les bilans hydriques et azotés. La croissance de la plante est basée sur l'interception lumineuse, la conversion en biomasse et la répartition de la biomasse formée dans les différents organes de la plante. Le bilan hydrique simule le contenu en eau du sol, le drainage et le lessivage. Le bilan azoté simule le stock d'azote minéral du sol en fonction des entrées par la fertilisation et des sorties par la demande de la plante et le lessivage. Des coefficients de stresses hydrique et azoté sont calculés et altèrent la croissance et le développement de la plante et du fruit.

L'élaboration de la qualité sera traitée dans le chapitre III qui sera divisé en deux parties. La première partie sera consacrée à la construction d'un modèle écophysiologique sur l'évolution du contenu en sucres durant la croissance de l'ananas, lié au modèle SIMPIÑA. Un modèle statistique décrivant la teneur en acides des fruits à la récolte en fonction des variables climatiques sera présenté dans la seconde partie de ce chapitre.

La conception de systèmes de culture proprement dite (Q3) sera développée dans le chapitre IV. Les deux modèles de qualité seront couplés au modèle décrit dans le chapitre II. Un module économique calculant le chiffre d'affaire du producteur sera développé. Le modèle sera utilisé pour concevoir des systèmes de culture qui optimisent les critères de production, de qualité, d'utilisation de la fertilisation azotée et économique. Les systèmes candidats sont comparés aux systèmes actuels (établis sur la base d'une typologie). Cette typologie a également été utilisée pour définir le champ des possibles exploré dans chaque zone de production et participer ainsi à la pertinence des systèmes proposés.

Le chapitre V sera consacré à la discussion générale et conclusion de ces trois questions de recherche.

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Chapitre II Construction d'un modèle de simulation du fonctionnement biophysique et d'élaboration du rendement de l'ananas

Ce chapitre repose sur l'article de revue publié dans *European Journal of Agronomy* et intitulé '**Validity of the pineapple crop model SIMPIÑA across the climatic gradient in Réunion Island**'.

Cet article présente la construction des modules soil et plante du modèle SIMPIÑA qui simule la croissance et le développement de l'ananas en fonction du climat et des pratiques culturales, permettant *in fine* d'avoir une estimation du rendement. Cette partie du modèle intègre 2 modules mécanistes : un module de croissance de la plante et du fruit, lié à un module sol qui simule les bilans hydriques et azotés (**Figure. II. A**). Des coefficients de stress sont estimés à partir des bilans hydriques et azotés et affectent la croissance et le développement de la plante et du fruit. Une analyse par suppression de mécanismes de stress a été utilisée pour tester comment les processus de stress influencent la capacité prédictive du modèle en fonction d'une large gamme de conditions climatiques. L'adéquation entre le niveau de complexité du modèle et la robustesse de ses prédictions sont discutées.

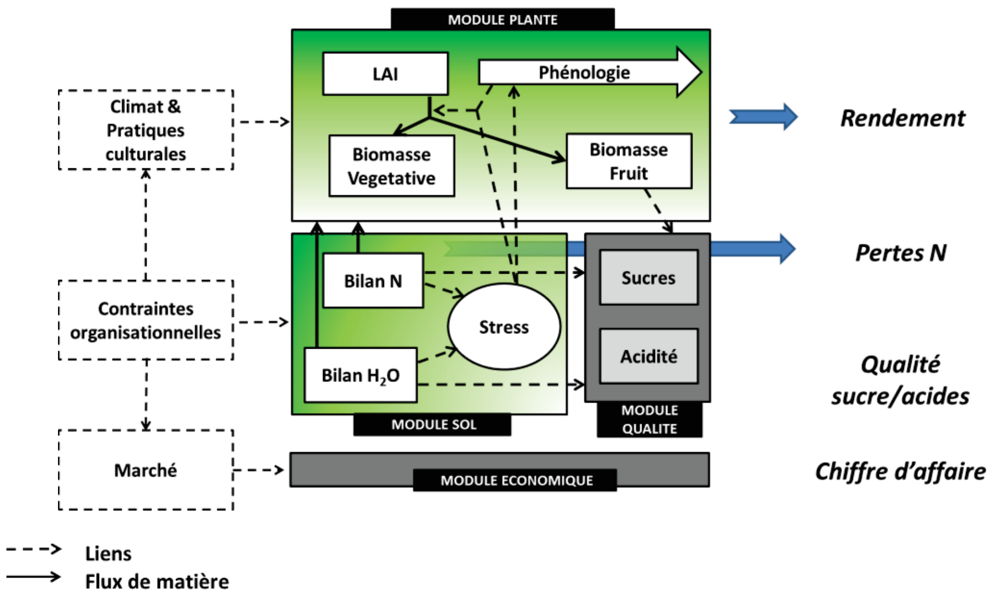

Figure II.A. Description des modules du modèle SIMPIÑA développé dans le chapitre II (en vert).

Validity of the Pineapple crop model SIMPIÑA across the climatic gradient in Réunion Island

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Abstract

Models used for designing cropping systems and for responding to cropping problems caused by climate variations must generate accurate predictions**.** Here, we describe the SIMPIÑA model, which simulates the development and growth of the 'Queen Victoria' pineapple cultivar and which accounts for stress resulting from nitrogen and water deficiencies. We present the calibration and the validation of SIMPIÑA with 15 independent data sets derived from experiments carried out on Réunion Island and covering wide ranges of climatic conditions and management practices. Comparison of simulations with data sets shows that the predictive accuracy of SIMPIÑA is very good, with relative RMSE values ranging from 0.06 to 0.19 for plant fresh biomass; such precision is sufficient for informing management decisions. Interestingly, there was no bias between observed and simulated values. A process-removal approach allowed us to determine how stress processes resulting from water or nitrogen deficiency influence the predictive capacity of the model across a broad range of climatic conditions. There was no clear trend for the effect of climate on model error in comparisons of the model with stress processes removed. When stress processes were partially removed from the model, fruit biomass error was particularly high when the effect of stress was removed from the radiation conversion efficiency and from biomass remobilization. Given its ability to correctly predict crop dynamics under contrasting conditions, SIMPIÑA appears to include the essential processes at the correct level of complexity.

Keywords: *Ananas comosus* (L.) Merr., Nitrogen stress, Water stress, Process-based model, Uncertainty

1. I. Introduction

Computer models are increasingly used by agronomists to design sustainable and innovative cropping systems for many different situations (Bergez et al., 2010; Loyce and Wery, 2006; Rossing et al., 1997). To predict crop performances, most crop models (e.g., CROPSYST, Stockle et al. (2003), DSSAT, Jones et al. (2003), APSIM, Keating et al. (2003), and STICS, Brisson et al. (1998)), are process-based and simulate soil–plant–environment interactions. In some cases, *ad hoc* models are developed to account for specific constraints on yield of particular crops or of production in particular contexts. In all cases, the predictive capacity of crop models is the core of their usefulness in agriculture. A crop model must be valid for many different situations to be useful for the design of cropping systems (Vermeulen et al., 2013), or the study of climate change effects (Laderach et al., 2011).

The validity domain of a model depends partly on the quality and quantity of data (including their range) used for model parameterization and evaluation and on the level at which processes are described (Affholder et al., 2012). Model complexity is not a guarantee of validity (Boote et al., 1996; Sinclair and Seligman, 1996), and which processes are included depends on model objectives (Affholder et al., 2012). Recently, researchers proposed the use of model reduction approaches to evaluate the adequacy of a model’s structure and to select the most appropriate level of complexity (Affholder et al., 2003; Cox et al., 2006; Crout et al., 2014; Crout et al., 2009; Kimmins et al., 2008). In addition to comparing observed and simulated outputs in order to assess the predictive capacity of a crop model, this approach attempts to elucidate the key processes that determine crop yield and the critical phases in the crop’s development under various cultural practices and climatic conditions.

In the current report, we describe and evaluate a model of pineapple production. Pineapple farms are high input systems that use large quantities of mainly nitrogen (N) fertilizers (Fournier, 2011), which can severely impact tropical environments. Water is also important at most stages of pineapple development (Combres, 1983), and irrigation is widely used. Optimizing the management of N fertilization and irrigation is thus important to pineapple farmers and to the environment. Such optimization requires an accurate, process-based model to simulate pineapple growth and development while accounting for differences and changes in mineral and water resources.

Pineapple ('Queen Victoria' cultivar) was the first fruit to be produced on Réunion Island, which is an island country located in the Indian Ocean, east of Madagascar. Pineapple is grown under a wide range of conditions on Réunion Island, where the elevation ranges from 50 m to 900 m a.s.l. and annual rainfall ranges from 500 mm to 5000 mm. Pineapple pests are nearly absent in the country, which makes it easier to assess the effects of water and N stresses on plant development and yield under different climatic conditions. Pineapple production on Réunion Island is thus very useful for investigating which processes and factors determine the validity of a crop model across a climatic gradient. An unusual feature of pineapple production on Réunion Island is that harvest occurs every month of the year because floral induction is controlled by the farmer.

Existing pineapple production models predict fruit development based on heat-units (Fleisch and Bartholomew, 1987; Fournier et al., 2010). A more comprehensive model was developed, the ALOHA-Pineapple model (Malezieux et al., 1994; Zhang, 1992; Zhang et al., 1997) based on the CERES-Maize model (Jones and Kiniry, 1986), which simulates the growth, development, and yield of the 'Smooth Cayenne' cultivar. However, this model was calibrated only in locations with low thermal variability and did not test low input scenarios.

In this paper, we present the SIMPIÑA model, which simulates the development and growth of the 'Queen Victoria' pineapple cultivar under various climatic conditions and N and water management practices on Réunion Island. The new model simulates water and nitrogen balances and estimates stress coefficients that affect pineapple growth and development. After developing the SIMPIÑA model based in part on published reports and on data derived from two experiments carried out in research station, we evaluated the accuracy of the model by comparing model outputs with data from 15 independent data sets covering a broad range of soil and climatic conditions. We then used a process removal approach to test how stress processes influence the predictive capacity of the model across a range of climatic conditions. Finally, we discuss whether the SIMPIÑA model has an appropriate level of complexity.

2. Materials and methods

2.1. Experimental data

The model was calibrated and tested with two independent data sets from Réunion Island. First, irrigation and fertilizer experiments were used to calibrate the model. Then, 15 independent data sets from different climatic zones (from 150 to 700 m a.s.l.) were used to test the model. All data sets used for calibrating and testing are presented in **Table II. 1**. In all experiments, temperature, rainfall, evapo-transpiration (ETP), and total radiation (Rg) were recorded with a Campbell Scientific™ meteorological station (Sheperd, UK), which was located beside the plot and at 1 m above the soil surface. When irrigation was applied, plots were drip irrigated under plastic mulch.

2.1.1. Calibration experiments with irrigation and fertilization

The calibration experiments with irrigation and fertilizer were conducted at the Bassin Plat Research Station on Réunion Island (see Table 1 for elevation and other background information). Plots used for irrigation and fertilizer experiments, which are described in the following paragraphs, were planted with 'Queen Victoria' pineapples in September 2011 on plastic mulch at a density of 88 000 plants ha^{-1}. Flowering was induced by applying ethephon (Ethrel, Bayer, SA) at 3 L ha^{-1}, 245 days after planting. In both experiments, one replicate corresponded to one ridge, with a specific sucker weight. The planted suckers weighed 275 g for one replicate, 225 g for two replicates, and 175 g for one replicate. Each month, eight pineapple plants were collected from each replicate and each treatment. Dry weight and fresh weight were determined for leaves, roots, stems, peduncles, inflorescences, fruits, and crowns. In addition, the number of fruitlets per fruit was determined. In both experiments, we measured 1920 plants and 960 fruits. Because control treatments (R) in irrigation and fertilizer experiments received the same amount of water and fertilizer (optimal irrigation and 300 kg of N ha^{-1}) and did not significantly differ between the two experiments (for plant weight at flowering induction, ANOVA p=0.41; for fruit biomass at harvest, ANOVA, p=0.98), we merged their data in the analyses.

Two irrigation treatments were tested in one calibration experiment: with drip irrigation (R), based on tensiometer readings and following technical recommendations

(Fournier, 2011), and without irrigation (I0). The pineapples were planted with standard fertilization of 300 kg of N ha^{-1} (i.e., 650 kg of urea) and 450 kg of potassium ha^{-1} (i.e., 900 kg of sulfate) following technical recommendations (Fournier, 2011). Of the total fertilizer applied, 20% was applied in solid form before planting, and the remainder was applied as a solution at 7, 12, 16, 20, 23, 26, and 28 weeks after planting.

Three N fertilization treatments were tested in a second calibration experiment: 300 (R), 150 (N150), and 0 (N0) kg of N ha^{-1}. Of the total fertilizer applied, 20% was applied in solid form before planting, and the remainder was applied as a solution at 7, 12, 16, 20, 23, 26, and 28 weeks after planting. Each treatment was drip irrigated based on tensiometer readings and following technical recommendations (Fournier, 2011).

Table II.1. Data sets used for calibration and validation of the SIMPIÑA model.

Location (and use)	Data sets[a]	Fertilization (kg N ha^{-1})	Irrigation	Elevation (m)	Year	Density (plants ha^{-1})	Annual rainfall (mm)	Number of data
Bassin Plat (55°29'20.64"E,21°19'21.62"S) (calibration)	R	300	yes	150	2012	88 000	556	676
	I0	300	no	150	2012	88 000	556	344
	N150	150	yes	150	2012	88 000	556	333
	N0	0	yes	150	2012	88 000	556	322
Bassin Plat (55°29'20.64"E,21°19'21.62"S) (validation)	P1	300	yes	150	2007	55 000	1050	96
	P2	300	yes	150	2007	110 000	1050	111
	P3	300	yes	150	2008	55 000	776	83
	P4	300	yes	150	2008	110 000	776	97
	P5	300	yes	150	2009	55 000	770	95
Tampon (55°32’21.06’’E,21°17’3.59’’S) (validation)	P6	300	no	650	2006	100 000	1871	112
Bassin Plat (55°29'20.64"E,21°19'21.62"S) (validation)	F1	300	yes	150	2007	98 000	1050	69
	F2	300	yes	150	2010	66 000	766	131
	F3	150	yes	150	2011	66 000	537	278
	F4	150	yes	150	2012	66 000	556	323
Bérive (55°31'10.59"E,21°17'10.21"S) (validation)	F5	300	no	550	2010	83 000	877	122
	F6	150	no	550	2010	83 000	877	124
Saint Benoit (55°42'12.86"E,21°05'53.85"S) (validation)	F7	300	no	340	2010	63 000	4005	90
	F8	150	no	340	2010	63 000	4005	104
	F9	300	no	275	2009	88 000	3616	72

[a]Notations in this column refer to treatments in the two calibration experiments (one concerning irrigation and the other concerning N fertilization) and to names of validation data sets.

2.1.2. Model testing data sets

As noted earlier, 15 experiments were used for model testing. Experiments P1 to P6 were used to determine the accuracy of vegetative growth predictions, and experiments F1 to F9 were used to determine the accuracy of predictions of fruit biomass at harvest and date of harvest (**Table II.1**). Pineapple plants were collected each month during the vegetative stage (during 6 to 8 months, depending on the year of planting and the elevation) in experiments P1 to P6, which were managed identically following the conventional techniques used on Réunion Island, i.e. optimal irrigation and 300 kg of N ha^{-1} (Fournier, 2011). A total of 594 plants were measured. Fruit biomass and date of harvest were determined in experiments F1 to F9 (but experiments F3 and F4 were used only for date of harvest because fruit biomass data were not collected), which were managed with one of two levels of N fertilization. Some “F experiments” received a standard fertilization of 300 kg of N ha^{-1}, and others received only 150 kg of N ha^{-1}. A total of 712 fruits were measured on 1313 harvest dates.

2.2 Model description

2.2.1. Model structure

SIMPIÑA was developed using STELLA® (software environment from High Performance System®, Lebanon, NH). Pineapple plant growth and fruit development at the field scale were simulated as affected by daily changes in soil N and soil water. Biophysical processes were determined according to three process-based modules, i.e., plant growth, water balance, and N balance. Pineapple development was divided into four stages: planting to initiation of dry matter production; the initiation of dry matter production to floral induction (artificially induced by the farmer); floral induction to flowering; and flowering to harvest. Flowering and harvest processes were determined based on a sum of degree days (SDD(t)) using a different base temperature for each development stage. The growth of pineapple was based on radiation interception, conversion to dry biomass (DM), and partitioning of DM into compartments: roots, leaves, stem, peduncle, inflorescence, fruit, crown, and suckers. After flowering, DM partitioning depended on the demand of each organ. DM of each organ was converted to fresh biomass (FM) to simulate pineapple yield. Model parameters, variables, and equations are presented in **Tables II.2**, **II.3**, and **II.4**, respectively.

Table II.2. SIMPIÑA model parameters.

Parameters	Unit	Description	Value	Source
SIMPIÑA-CROP				
Tb_f; Tb_{rec}	°C	Base temperature for physiological development stage (from planting to flowering/ from flowering to harvest)	8.34/ 9.24	Fournier et al. (2010); Léchaudel et al. (2010)
SDD_{fif}	°C d	Thermal time interval from floral induction to flowering	813	Fournier (pers. Com.)
$a_{h;}$ b_h	°C d;°C d ha plant	Parameter of SDD_h as function of density	1298; 1.7	Léchaudel et al. (2010)
GR	Days	Time from planting to biomass production initiation	25	Calibrated
aGR	D	Growth delay parameter	3	Calibrated
Eb	g MJ^{-1}	Light energy conversion efficiency (from planting to biomass production/ from biomass production to floral induction/ from floral induction to flowering;/ from flowering to harvest stages).	0.8/ 1.6/ 1.6/ 2	Calibrated
TSDDEb	°C d	Threshold of sum of degree-day for Eb initiation	600	Calibrated
pEbW	%	Percentage of decrease in light energy conversion efficiency after water stress	50	Calibrated
pEbN	%	Percentage of decrease in light energy conversion efficiency after N stress	35	Calibrated
pREM	%	Percentage of potential biomass remobilization	10	Calibrated
LOSSsuckini	g gDM^{-1}	Initial sucker rate decrease	0.02	Calibrated
Ea	-	Maximum interception efficiency	0.95	Varlet-Grancher et al. (1989)
Ec	-	Proportion of PAR intercepted	0.48	Gosse et al. (1986)
K	-	Extinction coefficient	0.3	Malezieux (1991)
SLA	m^2 g^{-1}	Specific leaf area	0.005	Observed
Ksen	LAI^{-1}	Senescence rate	0,001	Calibrated
ALro	-	Fraction of dry biomass allocated to roots	0.018	Observed
aALstem; bALstem;cALstem	-	Parameters of dry biomass allocated to stem as function of SDD(t)	$2.92.10^{-6}$; 0.0193; 40	Observed
ALped	-	Fraction of dry biomass allocated to peduncle	0.15	Observed

ALinf	-	Fraction of dry biomass allocated to inflorescence	0.12	Observed
Psurplus	%	Percentage of remaining assimilates allocated to leaves/stem	70/ 30	Calibrated
aNF; bNF	-	Parameter of fruitlet number as a function of FM_{fi}	- 2224.41; 12.44	Malezieux (1988)
RGR	$g\ g^{-1}\ °C\ d^{-1}$	Relative fruit growth rate	0.002524	Observed
maxDMfruilet	gDM	Maximal dry fruitlet biomass	0.12; 4.05	Observed
Wcont	$g\ g^{-1}$	Water content of crown/inflorescence/peduncle/roots/initial sucker planted/sucker	0.86/0.88/0.88/0.6/0.83/0.86	Observed
aWstem,bWstem,cWstem	-	Parameters of stem water content as function of SDD(t)	$-1.82.10^{-8}$;$1.26.10^{-4}$; 0.66	Observed
iniWfruit	-	Initial fruit water content	0.86	Observed
aWfruit,bWfruit	-	Parameters of fruit water content as function of SDD(t)	$-2.60.10^{-6}$; $1.30.10^{-3}$	Observed
minWleav,maxWleav	-	Minimal/Maximal leaf water content	0.8;0.86	Observed
TSDDWleav	°C d	Threshold of sum of degree-day for Wleav (t)	2900	Calibrated
aDEMcrown,bDEMcrown	-	Parameters of crown demand as a function of DMfruit (t)	0.14; 0.69	Observed
aDEMsuck,bDEMsuck	-	Parameters of sucker demand as a function of SDD (t)	0.0148; 0.004	Observed
piniWfruit	%	Percentage decrease in initial fruit water content	5	Observed
pbWfruit	%	Percentage decrease in fruit water content parameter	2,5	Observed
pREM	-	Fraction of dry biomass potentially remobilized at step 't'	0.1	Calibrated
SIMPIÑA –WATER				
kR	-	Rainfall infiltration coefficients (before 60/ between 60 and 120/ after 120 days after planting)	0.4/ 0.5/ 0.8	Combres (1983)
LAI_{mid}	$m^2\ m^{-2}$	Threshold of LAI for rainfall interception	5	Calibrated
aLAI, bLAI, cLAI	-	Parameters of Rint as a function of LAI(t)	0.0559; -0.2028; 1.168	Calibrated
pTAW	%	Percentage of total soil water content readily available	50	Combres (1983)
Kc	-	Crop coefficient	0.35	Allen et al. (1998)
pZr	-	Roots depth parameter	0.3	Calibrated
SIMPIÑA –NITROGEN				

kL	-	Leaching coefficient	0.1	Calibrated
Npot	g g^{-1} DM	Potential N content	0.013	Py et al. (1984)
Tstress	-	Threshold of daily stress	0.5	Calibrated
Tstresssum	-	Threshold of sum of stress	35	Calibrated

Table II. 3 Description of variables of the SIMPIÑA model.

Variables	Unit	Description
SIMPIÑA-CROP		
SDD(t)	°C d	Sum of degree-days at step (t)
SDD_{fh}	°C d	Thermal time interval between flowering and harvest
$SDD_f(t)$	°C d	Sum of degree-days from flowering stage at step (t)
D	plant ha^{-1}	Planting density
T(t)	°C d	Temperature at step (t)
ΔDM(t)	gDM $plant^{-1}$	Dry biomass newly formed at step (t)
PARi(t)	MJ m^{-2}	Photosynthetically active radiation intercepted at step (t)
RG(t)	MJ m^{-2}	Total radiation at step 't'
LAI(t)	m^2 m^{-2}	Total leaf area index at step (t)
kLAI(t)	m^2 m^{-2}	Leaf area for rainfall interception (t)
DMsuckini(t)	gDM $plant^{-1}$	Dry biomass of initial sucker planted at step (t)
ALleav(t)	-	Fraction of dry biomass allocated to leaves at step (t)
FM_{fi}	g $plant^{-1}$	Fresh biomass at floral induction
NF	-	Number of fruitlets per fruit
DEMfruit(t)	gDM $plant^{-1}$	Fruit demand at step (t)
DMfruitlet(t)	gDM $plant^{-1}$	Dry biomass of fruitlet at step (t)
DMfruit(t)	gDM $plant^{-1}$	Dry biomass of fruit at step (t)
DEMsuck(t)	gDM $plant^{-1}$	Sucker demand at step (t)
DEMcrown(t)	gDM $plant^{-1}$	Crown demand at step (t)
DMstem(t)	gDM $plant^{-1}$	Stem dry biomass at step (t)
DMleav(t)	gDM $plant^{-1}$	Leaf dry biomass at step (t)
Wleav(t)	g gFM^{-1}	Leaf water content at step (t)
Wstem(t)	g gFM^{-1}	Stem water content at step (t)
Wfruit(t)	g gFM^{-1}	Fruit water content at step(t)
IGR	days	Time interval to initiation of dry matter production
SIMPIÑA -WATER		
SW(t)	mm	Soil water stock at step (t)
D(t)	mm	Drainage at step (t)
I(t)	m^{-3}	Irrigation at step (t)
R(t)	mm	Rainfall at step (t)
Rint(t)	mm	Rainfall intercepted in the leaf axils (t)
ET(t)	mm	Evapotranspiration at step (t)
TAW(t)	mm	Total available soil water content at step (t)
RAW(t)	mm	Readily available soil water content at step (t)
Fc	-	Field capacity
PWP	-	Permanent wilting point
Zr(t)	mm	Root depth at step (t)
MET(t)	mm	Maximal evapotranspiration at step (t)
ETo(t)	mm	Potential evapotranspiration at step (t)
Wstress(t)	-	Water stress at step (t)

Wstresssum(t)	-	Cumulative water stress at step (t)
SIMPIÑA -NITROGEN		
F(t)	kgN ha^{-1}	Mineral N fertilized at step (t)
MINSOIL(t)	kgN ha^{-1}	Soil mineral N at step (t)
S(t)	kgN ha^{-1}	N mineralized from soil organic matter at step (t)
U(t)	kgN ha^{-1}	Mineral N uptake at step (t)
L(t)	kgN ha^{-1}	Mineral N leached at step (t)
SON	kgN ha^{-1}	Soil organic N content
k2	-	Parameter of mineralization of soil organic nitrogen content
Nstress(t)	-	Water stress at step (t)
Nstresssum(t)	-	Cumulative water stress at step (t)

With t the time step of the model in days.

Table II. 4. Principal equations of the SIMPIÑA model.

N°	Equation
1	$\Delta DM(t) = Eb \cdot PARi(t)$
2	$PARi(t) = Ea \cdot Ec \cdot RG(t) \cdot (1- \exp(-K \cdot LAI(t)))$
3	$LAI(t) = LAI(t-1) + (SLA \cdot DMleav(t)) – LAI(t-1) \cdot ksen$
4	$ALstem(t) = aALstem \cdot SDD(t)^2 – bALstem \cdot SDD(t) + cALstem$
5	If $(SDD_f(t)=0)$ Then $\{ALleav(t) = 1 - (ALro + ALstem(t))\}$ Else $\{ALleav(t)=1 - (ALro + ALstem(t) + ALped + ALinf)\}$
6	$DEMfruit(t) = RGR \cdot DMfruitlet(t) \cdot (SDD(t) - SDD(t-1)) \cdot (1 - (DMfruilet(t) / maxDMfruitlet)) \cdot NF$
7	$demCROWN(t) = (aCROWN \cdot biomsFRUIT(t) + bCROWN) - (aCROWN \cdot biomsFRUIT(t-1) + bCROWN)$
8	If $(SDD_f(t) = 0)$ Then $\{DemSUCK = (aSUCK \cdot SDD(t) – aSUCK \cdot SDD(t-1)\}$ Else $\{DemSUCK = 0\}$
9	$SDD_{fh} = a_h + (b_h \cdot d)$
10	$Wstem(t) = aWstem \cdot SDD(t)^2 + bWstem \cdot SDD(t) + cWstem$
11	If $(SDD(t) < TSDDWleav)$ Then $\{Wleav(t) = maxWleav – (maxWleav – minWleav) / TSDDWleav \cdot (TSDDWleav - SDD(t))\}$ Else $\{Wleav(t) = maxWleav\}$
12	If $(SDD_f(t) = 1)$ Then $\{Wfruit(t) = iniWfruit + (aWfruit \cdot SDD_f(t) + bWfruit)\}$ Else $\{Wfruit(t) = aWfruit \cdot SDD_f(t) + bWfruit\}$
13	$SW(t) = SW(t-1) + I + R - ET$
14	$TAW(t) = (Fc - PWP) \cdot Zr(t)$
15	$Zr(t) = pZr \cdot FM(t)$ $\{$ with $Zrmin < Zr(t) < Zrmax \}$
16	$RAW(t) = pTAW \cdot TAW(t)$
17	$Rint(t) = kLAI \cdot R(t) \cdot kR$
18	If $(LAI(t)<LAI_{mid})$ Then $\{kLAI = 1\}$ Else $\{kLAI = aLAI \cdot LAI(t)^2 – bLAI \cdot LAI(t) + cLAI\}$
19	$MET(t) = kc \cdot ETo(t)$
20	$ET(t)=MET(t) \cdot Wstress(t)$
21	If $(SW(t) <= RAW(t))$ Then $\{Wstress(t) = SW(t) / RAW(t)\}$ Else $\{Wstress(t) = 1\}$
22	If $(SW(t)>RAW(t))$ Then $\{D(t) = SW(t) - RAW(t)\}$ Else $\{D(t) = 0\}$
23	$MINSOIL(t) = MINSOIL(t-1) + F(t) + S(t) - U(t) - L(t)$
24	If $(TAW>0)$ Then $\{L(t) = MINSOIL(t) \cdot (1 - \exp(- kL \cdot (D(t) / TAW))\}$ Else $\{L(t) = 0\}$
25	If $(MINSOIL(t) < (\Delta DM(t) \cdot Npot)$ Then $\{U(t)=MINSOIL(t)\}$ Else $\{U(t) = (\Delta DM(t) \cdot Npot)\}$

26 If (ΔDM(t) . Npot = 0)
Then {Nstress(t) = 1}
Else {Nstress(t) = (U(t) / (ΔDM(t) . Npot)}
27a IGR = GR + (aGR . Wstresssum (t))
b If (TIME< IGR & Wstress(t)<TWstress)
Then {LOSSsuckini=1}
Else {LOSSsuckini=0}
c If (Wstress(t) or Nstress<TWstress) & (Wstresssum(t) or Nstresssum(t) > Tstresssum)
Then {ΔDM(t) = Eb.pEbW . PARi(t) or ΔDM(t) = Eb.pEbN . PARi(t)}
Else {ΔDM(t) = Eb. PARi(t)}
d If (Wstresssum(t) > Tstresssum)
Then { Wfruit(t) = iniWfruit . piniWfruit + (aWfruit . SDD_f(t) + bWfruit)}
Else { Wfruit(t) = iniWfruit + (aWfruit . SDD_f(t) + bWfruit)}

e If (Nstresssum(t) > Tstresssum)
Then { Wfruit(t) = iniWfruit + (aWfruit . SDD_f(t) + bWfruit . pbWfruit)}
Else { Wfruit(t) = iniWfruit + (aWfruit . SDD_f(t) + bWfruit)}

f If (DEMfruit > ΔDM(t)) & (Wstresssum(t) or Nstresssum(t) > Tstresssum)
Then {DEMfruit(t) = DMfruit(t-1) + ΔDM(t) + pREM . (DMleav(t) + DMstem(t))}
Else {DEMfruit(t) = DMfruit(t-1) + ΔDM(t)}

2.2.2. Pineapple growth and development module: SIMPIÑA-CROP

Pineapple fresh biomass (gFM) is simulated in three steps: i) estimation of dry matter production by the leaves; ii) dry matter partitioning between organs; and iii) accumulation of water stock in each organ. Dry matter production was calculated according to Monteith's equation (Monteith, 1972) (**Eq. 1**).

Dry matter production was initiated after a number of days calculated (IGR) since planting. The light energy conversion efficiency (Eb) varies according to phenological stage. The quantity of dry matter produced was calculated based on the radiation intercepted by the pineapple (**Eq. 2**). The leaf area index (LAI(t)) was calculated with a constant specific leaf area multiplied by the foliar biomass newly produced at each time step. LAI(t) was reduced by senescence (Eq. 3). Initial foliar biomass is set to the dry sucker biomass at planting.

Biomass newly produced was allocated to roots, stem, and leaves from planting to floral induction, and to peduncle and inflorescence from floral induction to flowering, with specific allocation coefficients and without priority rules (**Table 2**). These coefficients were constant for roots, peduncle, and inflorescence whereas the biomass allocated to the stem and leaves varies with the sum of degree-days (**Eq. 4 and 5**). At flowering, the biomass newly produced was allocated to fruit, crown, and sucker according to their demand with a priority to fruit. The remaining daily biomass produced was partitioned into leaves and stem according to a coefficient of partitioning (psurplus). Fruit demand was calculated as the demand of a fruitlet multiplied by the number of fruitlets per fruit. As demonstrated by Malézieux (1988), the number of fruitlets was estimated from an asymptotic function of fresh vegetative biomass at floral induction. We assumed that no competition occurred between fruitlets in pineapple fruit, as suggested by the absence of a relationship between fruitlet biomass and number of fruitlets in a fruit (Prudent et al., 2012). Fruitlet demand was simulated by a potential sigmoidal growth curve as proposed for other fruits (Léchaudel et al., 2005; Lescourret et al., 1998) (**Eq. 6**). We assumed a linear relationship between crown demand and fruit growth because crown removal has no effect on fruit growth (Chen and Paull, 2009) (**Eq. 7**). We assumed that the crown is not a source of carbohydrates for fruit growth. Sucker demand changed as a function of SDD(t) (**Eq. 8**). The harvest, which occurs when SDD(t) rises a threshold (SDD_{fh}) that depends on planting density (**Eq. 9**).

The dry matter of each organ was converted to fresh matter by adding a volume of water, which depends on the dry biomass newly formed per organ and the specific water content per organ. Stem, leaves, and fruit water contents varied as a function of SDD(t) after planting for stem and leaves and after flowering for fruit (**Eq. 10**, **11**, **and 12**).

2.2.3. Water balance module: SIMPIÑA-WATER

The SIMPIÑA-WATER water balance module simulates soil water content, drainage, and run-off. The soil was considered to be a water reservoir that is increased by rainfall and irrigation and decreased by crop evapotranspiration, drainage and run-off (**Eq. 13**). Total available soil water content for the crop (TAW) varied between soil water content at the field capacity and soil water content at the permanent wilting point (**Eq. 14**). TAW increased with root depth (Zr) (**Eq. 15**). The readily available soil water (RAW) in the root zone was that fraction of the total available soil water content that the crop can extract without suffering water stress (**Eq. 16**). Water inputs were defined as the sum of rainfall (Ra(t)) and irrigation (I(t)). The water balance calculated accounted for the following characteristics of pineapple systems: the design of pineapple leaf arrangement allows the canopy to retain a significant quantity of water in the leaf axils after rainfall. Once the plants grow and the canopy covers both mulch surface and the open areas, more rain water is captured by the plants and funneled to the plastic mulch **(Eq. 17, 18)**. Moreover, the use of plastic mulch reduced soil evaporation (Dusek et al., 2010). Thus, water input linked to rainfall was calculated from rainfall incorporated into the soil according to an infiltration coefficient, which varied from 0.4 at planting to 0.8 from 4 months after planting to harvest (Combres, 1983). Rainfall not incorporated into the soil corresponded to a volume of water run-off. Water outputs were defined by: evapotranspiration (ET(t)), which was based on: the reference evapotranspiration, a crop coefficient, kc; and a water stress coefficient, Wstress(t) (**Eq. 19, 20**). The water stress coefficient was calculated using the ratio between readily available soil content (RAW) and soil water content (**Eq. 21**). When the water content exceeded TAW, drainage occured (**Eq. 22**).

2.2.4. N balance module: SIMPIÑA-NITROGEN

The N balance module was adapted from the model proposed by Dorel et al. (2008). It simulates at a daily step the mineral N dynamics in soil based on fertilization and soil organic matter mineralization as inputs and crop uptake and leaching as outputs (**Eq. 23**). Given the soil characteristics typical in pineapple production, we assumed that N volatilization and denitrification were negligible and could be ignored (Payet et al., 2009; Stevenson, 1994). We considered that only mineral fertilizers are applied and that N from fertilizers is transferred to soil mineral N at time of application. The quantity of mineral N produced by soil organic matter mineralization was a function of soil organic N content. The quantity of mineral N that is leached was calculated at a daily step using an adaptation of the equation of the NLEAP model designed by Schaffer et al. (1994) (**Eq. 24**). The potential plant N concentration at step t was calculated as a function of crop dry matter according to the curve of N dynamics related to dry biomass proposed for pineapple by (Py et al., 1984). Potential plant N concentration was used to determine the daily crop N demand. We assumed that crop N uptake is driven by crop dry matter production as simulated by the SIMPIÑA-CROP module (**Eq. 25**). The N stress coefficient was calculated as the ratio between N demand and N uptake (**Eq. 26**).

2.2.5. Effects of water and N stress in the SIMPIÑA-CROP module

Water and N stresses altered both pineapple growth and development. We used the daily stresses (Wstress(t) and Nstress(t)) and the sum of daily stress values between planting and time step t (Wstresssum(t) and Nstresssum(t)) to represent an effect of the accumulation of stresses during development. Stresses were considered to have effects only when they exceed a threshold (Tstress and Tstresssum). The following seven growth and development parameters were altered by water and N stresses:

- The parameter aGR, which was a function of Wstresssum(t), extends the interval between planting and beginning of growth as expressed in the variable IGR **(Eq. 27a);**
- The rate of initial sucker decrease (LOSSsuckini) was activated when Wstress(t) is < TWstress during IGR **(Eq.27b)**;
- The light energy conversion efficiency (pEbW and pEbN) was decreased when Wstress(t) or Nstress(t) was < TWstress from planting to floral induction and when Wstresssum(t) or Nstresssum(t) was > Tstresssum from floral induction to harvest. Because the effects of stresses on the value of Eb were not cumulative, the minimum Eb value calculated was used if the two stresses occur at the same time **(Eq.27c)** ;
- piniWfruit decreased the initial fruit water content (iniWfruit) when Wstresssum(t) > Tstresssum **(Eq.27d)**;
- pbWfruit decreases the bias parameter of fruit water content equation (bWfruit) when Nstresssum(t) > Tstresssum **(Eq.27e)**;
- To satisfy fruit demand, dry biomass may be remobilized first from leaves (pREM) and from stem if was is not sufficient. Remobilization is only activated when Wstresssum(t) or when Nstresssum(t) > Tstresssum. Consequently, the dry biomass of leaves and the stem could decreased after flowering **(Eq.27f)**.

2.2.6. Model calibration

Most parameters were based on published information (**Table 2**). Eb, pZr, TSDD, TSDDWleav, ksen, GR, aGR, LOSSsuckini, pEbW, pEbN, pREM, psurplus, kL, Tstress, and Tstresssum were estimated using an iterative procedure to minimize the root mean square error (RMSE) of the pineapple vegetative biomass and fruit biomass over treatments.

2.3. Model evaluation

2.3.1. Statistical analysis

We compared the observed and predicted values of plant weights during vegetative growth for data sets P1 to P6, and of fruit biomass and date of harvest for data sets F1 to F9. The accuracy of model predictions was evaluated through the relative root mean squared error (RRMSE) (Kobayashi and Us Salam, 2000), which is a common criterion to quantify the mean difference between simulation and measurements:

$$\mathrm{RRMSE} = \frac{\sqrt{\frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{y_i} - \hat{\mathrm{y}}_\mathrm{i})^2}}{\bar{\mathrm{y}}}$$

where y_i is the observed value, $\hat{y}_i$ the corresponding simulated value, N the number of observed data, and $\bar{\mathrm{y}} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{\mathrm{y_i}}{\mathrm{N}}$ the mean of observed values.

2.3.2 Sensitivity analysis

We analyzed the sensitivity of the model to each parameter using climatic and management inputs of the control treatment (R). Sensitivity to model parameters was investigated for plant biomass at floral induction and for fruit biomass at harvest. The model was considered sensitive to a parameter when a 20% change in the parameter’s value changed model output for vegetative or fruit biomass by > 3%. This threshold was chosen according to expert and because it is an acceptable threshold for farmers to manage their crop.

2.3.3 Importance of water and N stress for the model’s predictive capacity

For all data sets (calibration and validation experiments), we compared fruit biomass at harvest between the full SIMPIÑA model and other versions of the model in which stress processes were removed. The comparison of models allowed us to assess the relative importance of stress processes on the predictive capacity of the model over contrasting climatic and cultural conditions. Two methods were used for these comparisons.

In the first method, fruit biomass at harvest (Y) was simulated after total removal of stress processes from three model formulations: (i) the full model (M); (ii) the model without water stress processes ($M0_W$); and (iii) the model without N stress processes ($M0_N$) (**Table 5**). The percentage of deviation (((Y_M-Y_{MO})·100)/Y_M) between fruit biomass (Y) simulated by M and fruit biomass simulated by $M0_W$ and $M0_N$ was determined. To test whether the predictive capacity of the model was altered by climatic variables, we analyzed fruit biomass errors (%) as a function of temperature, total radiation, evapotranspiration, and rainfall.

In the second method, fruit biomass at harvest (Y) was simulated after partial removal of stress processes. This was accomplished by separately removing each parameter in the model affected by water stress and N stress (aGR, LOSSsuckini, pEbW, pEbN, piniWfruit, pbWfruit, and pREM) in models M1 to M7 (**Table II. 5**). The percentage of deviation (fruit biomass errors) between fruit biomass simulated by model M (no processes removed) and models M1 to M7 (partial removed) was also compared for treatments sorted by level of N fertilizer and climatic area of production (dry, dry irrigable, humid).

Table II. 5. Summary of stress parameters removed in reduced models from the SIMPIÑA model.

Model	Model parameter						
	aGR	LOSSsuckini	pEbW	pEbN	piniWfruit	pbWfruit	pREM
M	-	-	-	-	-	-	-
$M0_W$	X	X	X	-	X	-	-
$M0_N$	-	-	-	X	-	X	-
M1	X	-	-	-	-	-	-
M2	-	X	-	-	-	-	-
M3	-	-	X	-	-	-	-
M4	-	-	-	X	-	-	-
M5	-	-	-	-	X	-	-
M6	-	-	-	-	-	X	-
M7	-	-	-	-	-	-	X

The signs '–' and 'X' indicate that the stress mechanism parameter was retained or removed, respectively. The value of remobilization parameter pREM is not null if N stress occurs in $M0_w$ or if water stress occurs in $M0_N$.

2. Results

3.1. Model calibration

An iterative procedure was used to determine the values of GR, ksen, ALrem, TSSWleav, TSDDEb, kL, Tstress, Tstressum, Eb, aGR, pEbW, pEbN, and pREM (**Table II. 2**). Observed and simulated dynamics of pineapple plant biomass and fruit biomass were similar for the three masses of suckers at planting and for the four water and N treatments (**Fig. I. 1**). Plant biomass and fruit biomass increased with sucker weight at planting, regardless of water and N treatments. Plant biomass and fruit biomass were lowest for I0 and F0 treatments. Relative RMSE values ranged from 0.06 to 0.15 for plant biomass and from 0.05 to 0.23 for fruit biomass.

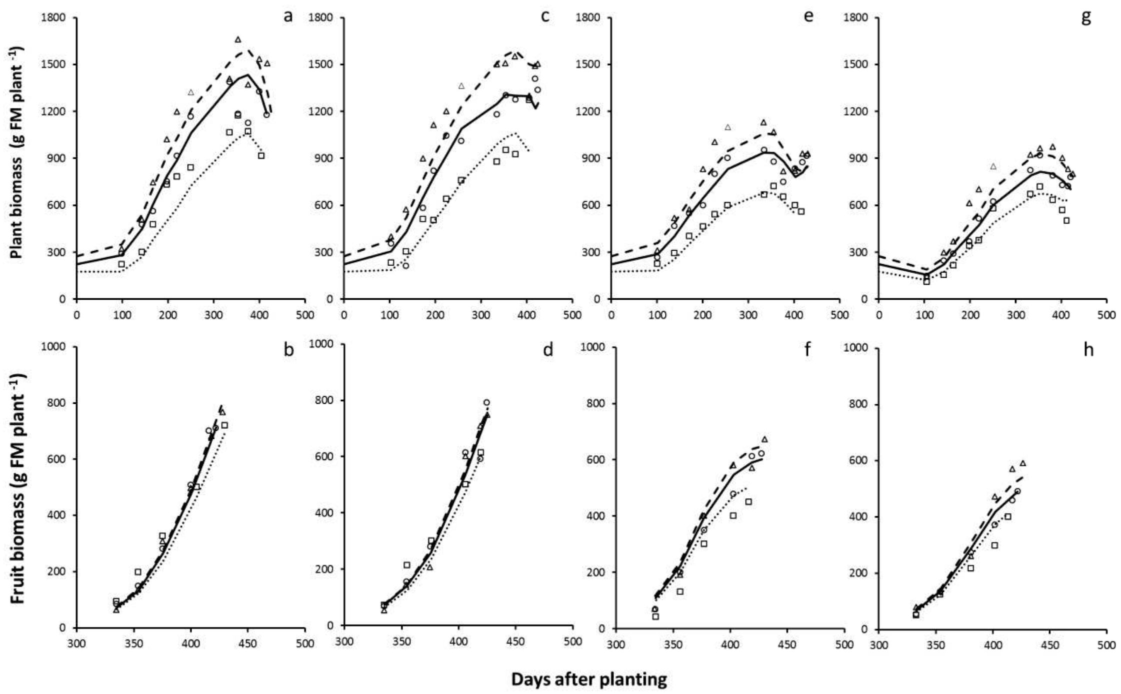

Figure 1. Simulated and observed data for fresh pineapple plant biomass and pineapple fruit biomass in the calibration experiments as affected by sucker weight at planting and by two water and two N treatments. Observed data are symbols, and simulated data are lines. FM = fresh mass. Sucker weight at planting was 175 g (□, dotted line), 225 g (○, solid line), or 275 g (∆, dashed line). The water and N treatments, which are summarized in Table 1, were R (a, b), N150 (c,d), N0 (e,f), and I0 (g,h).

3.2. Model evaluation

When evaluated with independent data collected under different weather conditions and planting densities, the model performed well in predicting the vegetative fresh biomass of the pineapple, with RMSE values ranging from 98 to 159 gFM plant^{-1}. The model had no bias, i.e., observed and simulated values were highly correlated, with a slightly underestimation (y = 0.94x, p < 2e-16, R^2=0.95) (**Fig. II.2**). Fruit biomass at harvest and date of harvest were also accurately simulated by the SIMPIÑA model over a wide range of weather conditions and planting densities, with RMSE values of 22 gFM fruit^{-1} for fruit biomass and 6 days for date to harvest (**Fig.II. 3a, 3b**).

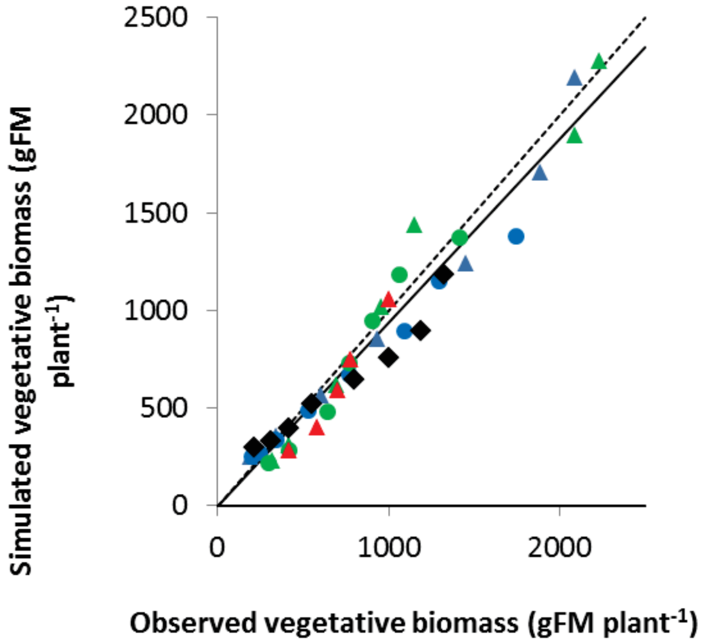

Figure II.2. Observed and simulated vegetative fresh biomass (gFM plant^{-1}) as affected by year (2006: black, 2007: blue, 2008: green, and 2009: red) and plant density (55,000 plant ha^{-1}: Δ , 100,000 plant ha^{-1} : ◊, and 110,000 plant ha^{-1}: ○). The solid line shows the functional regression (y=0.94x, R^2=0.95). The dotted line is the 1:1 line.

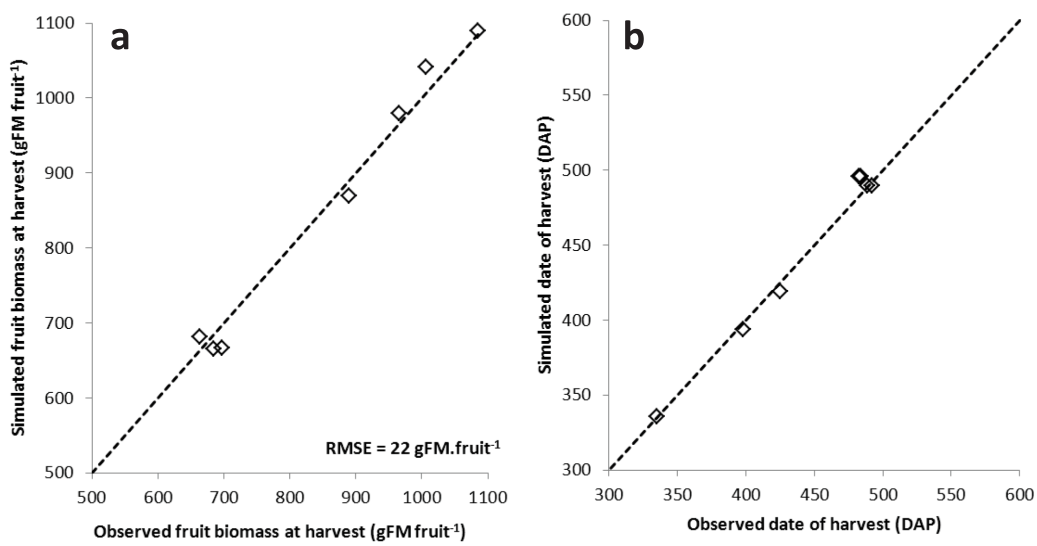

Figure II. 3. Observed and simulated (a) pineapple fruit fresh biomass at harvest (gFM) and (b) date of harvest. DAP = day after planting. The dotted line is the 1:1 line.

3.2.1 Sensitivity analysis

Vegetative biomass at floral induction was sensitive to the parameters related to crop characteristics (crop coefficient, kc), phenology (time from planting to biomass production initiation, GR; threshold of Eb initiation from planting to floral induction stage, TSDDEb), organ water content (TSSDWleav), and stress (threshold of daily stress, Tstress; growth delay parameter, aGR; and initial sucker rate decrease, LOSSsuckini) (**Fig. II. 4a**). Fruit biomass at harvest was also sensitive to parameters related to biomass production (relative growth rate, RGR; extinction coefficient, k), phenology (base temperatures, Tb_f and Tb_{rec}; time from planting biomass production, GR; and sum of degree-day between floral induction to flowering, SDD_{fif}), water stock (parameter of fruit water content, aWfruit), and stress (threshold of daily stress, Tstress) (**Fig. II. 4b**).

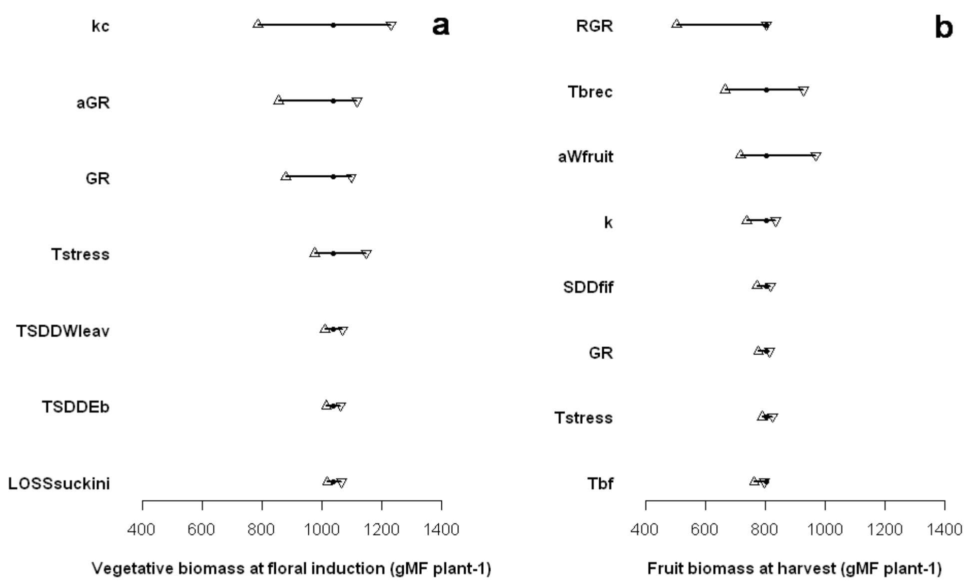

Figure II. 4. Analysis of model sensitivity to parameters: Mean (•) and values after -20% (∆) and +20% (∇) variations in each model parameter of the (a) vegetative fresh biomass at floral induction and (b) fruit fresh biomass at harvest. Only parameters that showed variations > 3% are presented.

3.2.2 Response of the model to removal of stress processes

Relative to the full model, the model without water stress processes ($M0_W$) had larger fruit biomass errors than the model without N stress processes ($M0_N$) (**Fig. II. 5**). There was no clear trend of the effect of climatic variables on error of $M0_W$ and $M0_N$ compared to the full model. Fruit biomass deviation was the same at low and high annual mean temperature. The effect of annual mean radiation on the errors was never monotonous with biggest errors at 18 and 20 MJ m-2. Concerning ETP, the biggest errors were observed when ETP was < 3.5 and > 4. Finally, the effect of annual mean rainfall showed no clear trend on fruit biomass deviation. Partial removal of stress processes indicated that fruit biomass error was particularly high when the effect of stress was removed from the radiation conversion efficiency (models M3 and M4) and from biomass remobilization (model M7) (**Table II.6**). Fruit biomass error was negative for model M7. For model M6, only one deviation was observed for N0 treatment. In model M4, fruit biomass error was high for experiments with a low level of N fertilizer in dry and irrigable climatic areas and in humid climatic areas (N0 and F8).

3. Discussion

Comparison of observed and predicted data for the calibration experiments demonstrated that the SIMPIÑA model correctly accounted for the effects of sucker weight at planting and the fertilization and irrigation treatments. Selecting the initial sucker weight is an important management option because it affects the foliar area that in turn determines the initiation of biomass production. We also note that the extreme treatments in the calibration experiments (no irrigation and no N) were simulated with very low errors in fruit biomass (relative RMSE values were 0.12 and 0.14, respectively).

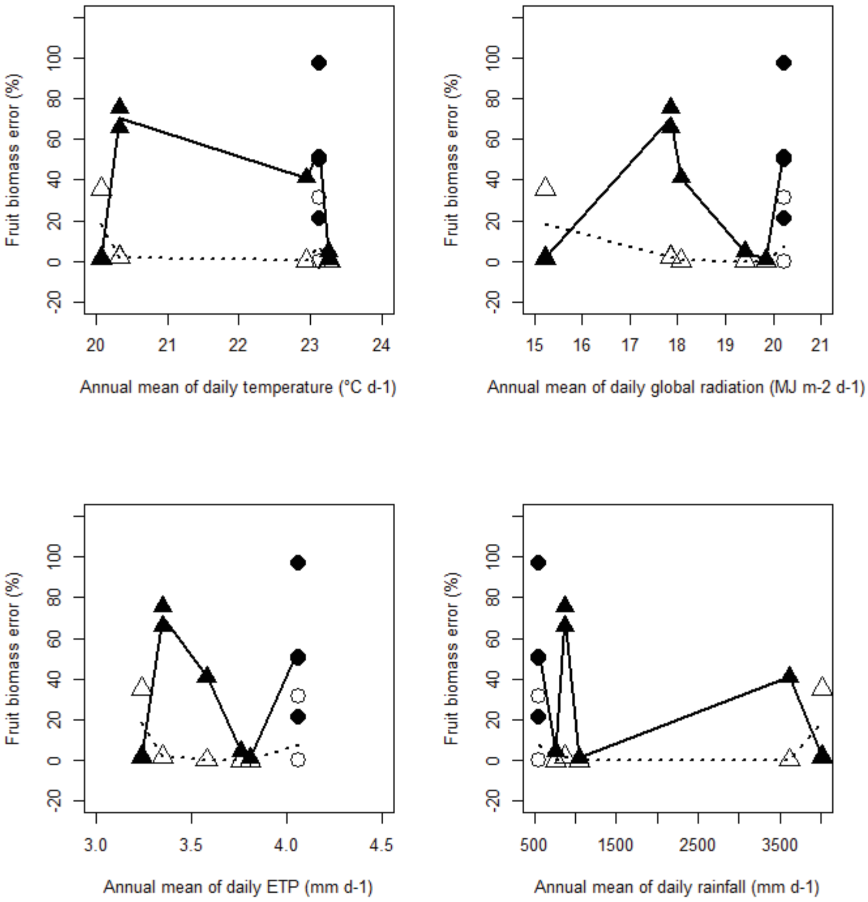

Figure II 5. Fruit biomass deviation (%) compared to the complete model (M0) for the model without water stress processes (model $M0_W$, black) and without N stress processes (model $NM0_N$, white) as a function of annual mean of daily (a) temperature, (b) global radiation, (c) ETP, and (d) rainfall. Circles represent the calibration experiments and triangles represent the validation experiments. Solid and dotted lines represent the mean value of fruit biomass deviation compared to model M0 for model $M0_W$ and $M0_N$, respectively.

In the validation simulations, there were good agreement between observations and simulations of vegetative plant biomass and fruit biomass at harvest under contrasting conditions of planting density, N fertilization, irrigation, and climate. The model accurately simulated the effect of planting densities, at a range observed in most production systems with others pineapple cultivars (De Souza et al., 2009; Malezieux, 1988), on pineapple growth and development. However, in order to valid the model for others cultivars, growth parameters would be adapted. Many parameters in literature are based on 'Smooth Cayenne' cultivar. As shown by Fournier et al. (2010), growth characteristics may differ between cultivar, i.e., number of leaves, the D leaf weight and the plant weight. Contrasted experiments with different cultivars and various fertilization and irrigation practices under a large range of climatic conditions are required to estimate others cultivars growth parameters in the model. We note that the model accounts for the density effect not by using a correction factor but by estimating interplant competition for radiation and soil resources. Even though the validation data sets covered a broad range of climatic and management effects, there was no bias between simulations and observations. The model accurately simulated the effects of cultural practices, i.e., sucker weight at planting, planting density, and N and water stress across a broad climatic gradient. Furthermore, the overall prediction accuracy was good, with relative RMSE values equal to 0.13 , 0.12, and 0.01 for vegetative biomass, fruit biomass, and date of harvest, respectively. Such accuracy is clearly sufficient to help farmers improve their management because cultural practices tested in this study represents the range of existing cultural practices.

Vegetative plant biomass was most sensitive to kc (crop coefficient), showing that water plays a major role in vegetative biomass production (Combres, 1983; Malezieux, 1988; Py, 1960). The crop coefficient varied during the cropping cycle and generally had three values depending on phenological stage (an initial value, an intermediate value, and a final value): such values can be quite different in sugar cane and other crops (Allen et al., 1998). The crop coefficient for pineapple exhibits only low variation during the three phenological stages and when the crop is grown on plastic mulch, the values were 0.4, 0.2, and 0.2 for the three phenological stages respectively (Allen et al., 1998). Another study also reported minimal variation in kc value over pineapple developmental stages (Carr, 2012).

Surprisingly, vegetative plant biomass was also particularly sensitive to parameters related to the delay in the start of biomass production after planting (aGR and GR). This shows that this initial step after planting is crucial and influences the entire vegetative growth period, as previously observed for strawberry (Palha et al., 2011). The threshold at which stress is considered to alter growth (Tstress) also greatly influences the production of vegetative biomass. For instance, the use of stress threshold coefficient strongly improved the prediction of banana crop growth in the SIMBA model (Ripoche et al., 2012). In a mango model, fruit biomass was less sensitive to RGR than to another parameter related to the early phase of fruit development, which was the initial fruit dry mass (Léchaudel et al., 2005). For several fruit species, the early phase of fruit growth is related to cell division and influences fruit mass at harvest (Bertin et al., 2002; Scorza et al., 1991). The extinction coefficient (k) also greatly affects fruit biomass in SIMPIÑA, showing that light interception is a major factor influencing biomass production. Overall, the sensitivity analysis in SIMPIÑA showed that biomass production relies on a variety of processes (light interception, stresses, fruit growth, and phenology) and is not dominated by a single process.

Table II. 6. Summary of fruit deviation error after partial removal of stress processes in models M1 to M7.

Data sets	**Fertilization (kg N ha^{-1})**	**Climatic area**	**Deviation error with water stress processes removed**				**Deviation error with N stress processes removed**		**Deviation error with all stress processes removed**
			M1	M2	M3	M5	M4	M6	M7
I0	300	dry	40	41	104	12	0	0	-22
F5	300	dry	19	23	69	13	0	0	-37
F6	150	dry	14	23	62	10	0	0	-38
F1	300	dry irrigable	0	0	0	0	0	0	0
F2	300	dry irrigable	0	4	0	0	0	0	0
R	300	dry irrigable	3	6	49	0	0	0	-3
N150	150	dry irrigable	3	44	76	0	0	0	-35
N0	0	dry irrigable	8	12	10	0	58	-2	-32
F9	300	humid	0	0	36	0	0	0	0
F7	300	humid	0	0	0	0	2	0	-12
F8	150	humid	0	0	0	0	57	0	-59

The stress parameters removed are listed in Table 5.

The removal of all stress processes from SIMPIÑA (in models $M0_w$ and $M0_N$, **Fig. 5**) resulted in large errors in the simulation of fruit biomass relative to the full model (model M0). The variation in the effect of removal was greater with water stress processes (model $M0_W$) than N stress processes (model $M0_N$). This result may be explained by the greater diversity in rainfall than in N fertilization in the 11 situations used for model testing. In fact, the absence of mineral N fertilization has been used only recently by a few farmers who are testing organic production. Rainfall, in contrast, varies greatly with the range in altitude on Réunion Island (from 0 to 900 m a.s.l.). However, there was no clear trend in fruit biomass error with climatic variables. This absence of trend when conditions diverge from those used in calibration suggests that stress can occur across the climatic gradient. It also suggests that cultural practices (irrigation and fertilization) can mitigate stress. Indeed, irrigation and fertilization were in interaction with stress processes thus the monotonous effect of climatic variables on the fruit biomass deviation was partially concealed.

By partially removing stress processes in the model, we attempted to increase our understanding of the effects of N and water stress processes on fruit biomass at harvest and to determine whether the model can be simplified. In half of the cases (**Table II. 6**), partial stress removal did not lead to error compared to the full model (model M0). This is in accordance with models $M0_W$ and $M0_N$ in that the effect of removal of water or N stress processes depended on the situation, suggesting that only certain processes are important and these differ depending on climatic area and cultural practices. Removing the effect of water stress on aGR (model M1) and on LOSSsuckini (model M2) clearly increased the error compared to model M0, especially under dry conditions. Although aGR and LOSSsuckini are both linked to the early phase of plant growth, the error was greater for M2, suggesting that water stress has a greater effect on loss of sucker weight than on the delay in the initiation of biomass production.

We also found that stress greatly affects the conversion of radiation into biomass, i.e., the removal of stress in models M3 and M4 results in high errors relative to model M0. Interestingly, the removal of stress effects on the remobilization of biomass (from leaves and stem to fruit) (model M7) led to negative errors compared to model M0. This means that for seven situations, predicted yield was lower with model M7 than with model M0. Even under conditions that seemed optimal, as in humid and dry irrigable areas, models lacking the reserve remobilization process underestimated fruit biomass. For the 'Smooth cayenne' cultivar, previous research found that foliar reserves constituted 60% of the carbon supply for fruit growth (Malezieux, 1988). This confirms the necessity of including the reserve remobilization process for fruit growth in the SIMPIÑA model. It is important to include all stress effects on model parameters in order to simulate a wide range of climatic conditions and cultural practices. Despite the absence of trends in the relationship between errors in fruit biomass predictions after removing stress processes and climatic conditions, especially rainfall, we note that brief stresses, like water stress on initial sucker weight, could greatly affect pineapple growth and development. Water stress could be an important source of yield loss when it occurs at a critical moment in crop development. Similar effects of water stress were observed at the early stages of foliar development of potato (Kashyap and

Panda, 2003). In our case, we therefore infer that we have not included too many processes in the SIMPIÑA model and that model reduction does not seem possible, which is contrary to other studies in which model simplification was possible (Crout et al., 2009). Actually we had shown that the removal of stress processes resulted in large errors in the simulations relative to the full model. Thus stress processes might be necessary to simulate with accuracy the growth and development of pineapple under a large range of climatic conditions and cultural practices. Some simplifications might be acceptable for specific uses of the model but the validity range of the model would be limited and the model could not be used for pineapple system management on Réunion Island.

4. Conclusion

We showed that the SIMPIÑA model accurately simulates pineapple growth and development across a substantial climatic gradient. The model evaluation showed that SIMPIÑA does not include needless processes. SIMPIÑA should allow pineapple growers to explore combinations of cultural practices (irrigation, fertilization, sucker masses at planting, planting density) under a diversity of conditions in order to optimize N and water resources while ensuring suitable yield.

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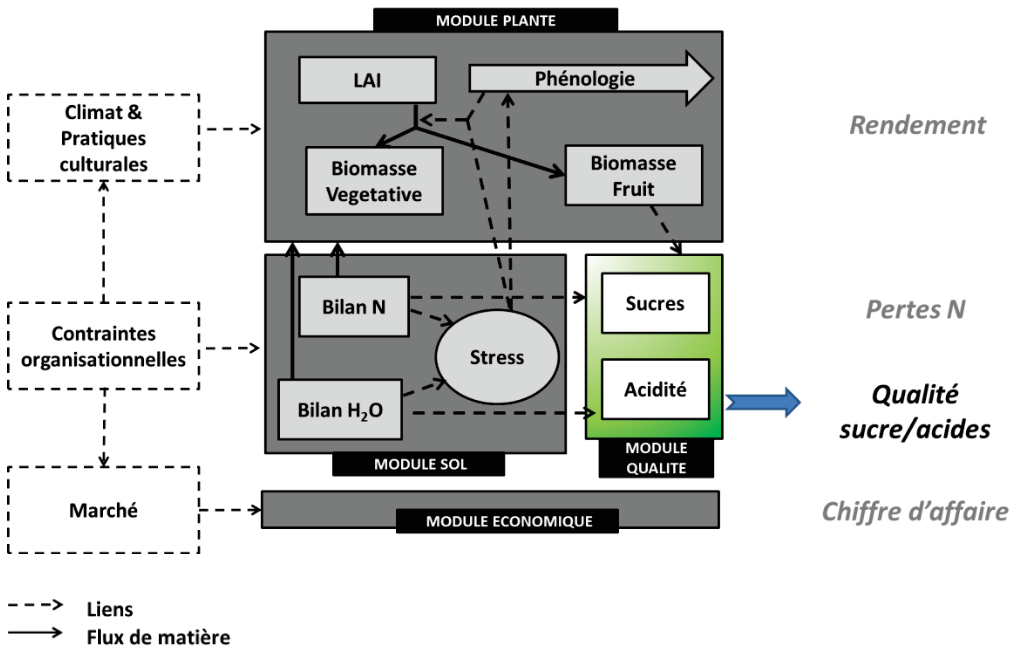
Chapitre III – Développement de module pour prédire la qualité de l'ananas à la récolte

Ce chapitre repose sur deux articles à soumettre. Le premier s' intitule '**Linking an ecophysiological and a crop model to predict the effects of agro-climatic conditions on the sugar content of pineapples'** à soumettre à European Journal of Agronomy**.** Cet article un modèle écophysiologique sur l'évolution du contenu en sucres durant la croissance de l'ananas. Ce modèle est lié au modèle plante décrit dans le chapitre II. Le deuxième article s'intitule '**Effect of climatic conditions on pineapple acidity at harvest '** à soumettre à Agricultural and Food Chemistry**.** Cet article présente un modèle statistique décrivant l'acidité des fruits à la récolte en fonction des variables climatiques. Ce modèle repose sur une approche originale qui permet d'identifier quelles sont les périodes durant lesquelles les variables climatiques (pluviométrie, rayonnement global et température) affectent l'acidité des fruits à la récolte. Les variables correspondant à l'intégration des variables climatique pendant les périodes les plus influentes sont ensuite agrégées dans un modèle linéaire généralisé permettant de prédire avec une précision de 61 % l'acidité des fruits. Ce GLM a été intégré au sein du modèle SIMPIÑA **(Figure III.A).**



FigureIII.A. Description des modules du modèle SIMPIÑA développé dans le chapitre III (en vert).

III. A. Linking an ecophysiological and a crop model to predict the effects of agro-climatic conditions on the sugar content of pineapples

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Abstract

A process-based model simulating the change in total soluble solids (TSS) in fruit flesh was developed to describe the effect of climatic conditions on the sugar content of 'Queen Victoria' pineapple at harvest. The ecophysiological model of soluble sugar accumulation was linked to SIMPIÑA, a crop model that accurately predicts the daily increases in flesh dry and fresh weight. When the process-based model and crop model were linked, the dry and fresh matter of the pineapple flesh, as affected by climatic conditions, could be used as inputs to predict the TSS at harvest. The ratio of carbon used for synthetizing compounds other than sugars was estimated during fruit growth. TSS were compared for harvested fruit grown under eight agroclimatic conditions. In the flesh of fruit harvested close to maturity, i.e., at 1400 degree-days after flowering, TSS were strongly related (r^2 = 0.55, P<0.001) to total soluble sugar content. The variability of TSS was substantial within each of the eight agroclimatic groups: standard deviations ranged from 0.93 to 1.5 °Brix. TSS values were highest for pineapples grown in dry locations without N deficiency. TSS values were lowest (< 17 °Brix) for pineapples grown under N-deficit conditions, regardless of soil water conditions. For data from 14 experiments conducted under different climatic conditions, N fertilization, and irrigation conditions, the model predicted the TSS at harvest with an RRMSE of 0.04. By linking this sugar model to the SIMPIÑA crop model, reseachers can account for the impact of environmental conditions and cultural practices on the growth and development of pineapple and can predict the variability in the gustatory quality of pineapple grown on Reunion Island.

Keywords: *Ananas comosus* (L.) Merr., quality, sugar content, SIMPIÑA model, process-based model

1. Introduction

Fruit quality has become increasingly important in fruit production, and improving the quality of products is an economic, public health, and scientific concern. The gustatory quality of fruit can be highly variable and difficult to manage (Basile *et al.*, 2007; Genard and Bruchou, 1992; Taylor *et al.*, 2007). Therefore, understanding fruit growth and the accumulation of compounds affecting gustatory quality has been a challenge for researchers. Predicting how these compounds accumulate in fruit is difficult because their accumulation is affected by the environment and by management.

Sugar content greatly affects the gustatory quality of fruit (Vaysse *et al.*, 2000). Sweetness depends on the concentration of sugar, which is synthesized and accumulated in the flesh during fruit growth (Leonard *et al.*, 1953; Prudent *et al.*, 2011; Robertson *et al.*, 1992). Fruit growth determines fruit weight and volume at harvest, and larger fruit obviously require more sugar than smaller fruit to achieve the same concentration of sugar. The pathways by which sugars accumulate differ among fruit species (Hubbard *et al.*, 1991). Sugar content, and more precisely the amount of carbon in sugars in the flesh, varies according to the supply of carbohydrates to the fruit; that supply depends on leaf photosynthesis and plant metabolism and is diluted by increases in fruit volume (Quilot *et al.*, 2004). As fruit volume increases, carbon and water enter the fruit via the xylem and phloem and exit the fruit via respiration and transpiration (Fishman and Genard, 1998; Génard *et al.*, 2003; Genard and Souty, 1996; Lescourret *et al.*, 2001).

Models of fruit quality range from simple equations that estimate fruit size and yield to a complex representation of respiration, photosynthesis, and assimilation of nutrients with the goal of predicting seasonal changes in concentrations of compounds involved in quality (Vazquez-Cruz *et al.*, 2010). Although the latter ecophysiological models simulate how environment and plant metabolism affect fruit mass, fruit volume, and sugar content, they seldom consider how water and nitrogen (N) balances affect vegetative growth and fruit quality. At the same time, several crop models have been developed that assess carbon partitioning in fruit trees as affected by water stress but that do not assess fruit quality (Allen *et al.*, 2005; Costes *et al.*, 2008). Sansavini (1997) proposed the combined use of a crop model and a fruit growth model for fruit quality to understand how crop management affects processes underlying crop performance. Recently, the Qualitree model was developed to simulate the vegetative growth and the development of fruit quality as affected by physiological processes and crop management (Lescourret *et al.*, 2011). This model has been used to evaluate the effect of water restrictions on fruit growth and also on sugar concentrations in peach fruit (Miras-Avalos *et al.*, 2013). Process-based fruit growth models are useful for understanding how fruit quality is affected by climate and management (Dai *et al.*, 2008), and their usefulness could probably be increased if they are linked to crop model simulates maize kernel moisture content, which is an important factor influencing the quality of maize grain, is part of a larger crop model that helps farmers decide when to harvest (Maiorano *et al.*, 2014). This kind of linkage should be useful for improving the quality, yield, and management of pineapple and other fruit crops.

Pineapple (*Ananas comosus*) is an economically important crop in tropical and subtropical areas, and fruit sweetness is a major factor determining the quality of pineapple fruit (Py *et al.*, 1984). Fruit sweetness gradually increases during the later stages of fruit growth (Bartholomew and Paull, 1986). Variation in pineapple fruit sugar content is associated with fruit maturation and growing conditions (Bartolome *et al.*, 1995; Py *et al.*, 1984; Singleton and Gortner, 1965). Pineapple ('Queen Victoria' cultivar) was the first fruit to be produced on Réunion Island, which is an island in the Indian Ocean, east of Madagascar. Pineapple is grown under a wide range of conditions in Réunion Island, where the elevation ranges from 50 m to 900 m a.s.l. and annual rainfall ranges from 500 to 5000 mm. The large variability in fruit size and quality makes it difficult to predict sugar content based on crop growth.

The aim of this study was to develop a simple model able to predict the content in total soluble solids of pineapple (TSS) at harvest linked with the SIMPIÑA crop model (Dorey *et al.*, 2015). Measurement of the percentage of TSS in °Brix is used extensively in commercial food manufacture to evaluate fruit sweetness. TSS are strongly correlated with sugar content in the ripe fruit of various species, including peach (Grechi *et al.*, 2008) and banana (Fernando *et al.*, 2014). We used TSS as an indicator of fruit quality in the model because it is used as an indicator of fruit quality in commerce (Grechi *et al.*, 2008). The sugar model developed in this study was partly based on the peach model of Quilot *et al.* (2004), which in turn was derived from the process-based SUGAR model developed for peach by Genard and Souty (1996) and Génard *et al.* (2003), and which was recently revised by Grechi *et al.* (2008). The latter models describe the daily changes in total soluble sugar content in peach flesh during the final stage of fruit growth until fruit harvest and the TSS at harvest under various growing and climatic conditions.

We first characterized the rate at which sugars are transformed into other compounds in pineapple flesh. Next, we calibrated the k parameter, which corresponds to the relative rate at which carbon in the sugars of fruit are used to synthesize compounds other than sugars. Then we evaluated the accuracy of the model by comparing TTS simulations with data from 14 independent data sets covering a broad range of climatic and cultural conditions. Finally, we analyzed the simulation of TSS at harvest for eight cropping systems representing different climatic and cultural conditions.

2. Materials and methods

2.1 Experimental data

Data set A was derived from four experiments carried out in 2007 (experiments E1 and S1) and 2008 (E2 and S2) at two locations that were planted with 'Queen Victoria' pineapple. Experiments E1 and E2 were conducted at 290 m a.s.l. in Saint Benoit, in the east of the island (55°42'12.86"E, 21°05'53.85"S), which is a very wet area with an average annual rainfall > 4,000 mm and an average temperature of 22.0 °C. Experiments S1 and S2 were located in the southwest of the island at CIRAD's Bassin Plat research station, located at 150 m a.s.l. (55°29'20.64"E, 21°19'21.62"S); this location has lower rainfall than the eastern area, with about 700 mm of rainfall per year and an average temperature of 22.7 °C. Each experiment was managed identically following the locally recommended cultural practices: calibrated suckers (250 $\pm$ 25 g) were planted under polyethylene mulch at a density of 89,000 plants ha^{-1}. The fields were fertilized with 300 kg ha^{-1} of nitrogen (i.e., 650 kg of urea) and 450 kg ha^{-1} of potassium (i.e., 900 kg of sulfate). Flowering was induced with ethephon (Ethrel; Bayer SA) at a rate of 3 L ha^{-1} when the plants had reached a weight of around 1.2 kg, i.e., an average "D" leaf weight of 55 g. The field located on the southwest part of the island was drip irrigated, and the soil water status was regularly checked with Watermark sensors (Irrometer Company, Riverside, CA). The field located on the eastern part of the island was not irrigated and only received natural rainfall.

Fruits were harvested at five developmental stages from 30 to 122 days after flowering. Flowering was defined as occurring when 50% of inflorescences in the studied field had at least one corolla visible. Flowering dates were December 2007, March 2009, February 2008, and April 2009 for experiments S1, S2, E1, and E2, respectively. The first three developmental stages were defined based on the sum of the thermal time after flowering rather than on peel color because the peel color of the pineapple was still green at these stages. The last two developmental stages were defined based on pineapple peel color because peel color reflects ripening at these stages. Fruits were harvested at about 706 (H1), 1121 (H2), 1275 (H3), and 1318 (H4) degree days, with 9.24°C as the base temperature (Léchaudel *et al.*, 2010). For the last two stages, fruits were harvested at the turning stage (H3), which corresponded to the beginning of changes in peel color, i.e., yellow for QV, and at a ripe stage (H4), which corresponded with the complete change in peel color. In each of the four experiments, six fruits were selected for stages H1 and H2, and 15 to 20 fruits were selected for the two last harvest stages (H3) and (H4).

After every harvest, the fresh mass of every fruit was measured with and without their crows. Then, the peel tissues of each fruit were excised, and pulp tissues were sub-sampled. A first sample of flesh was mixed using a Grindomix blender (Retsch, Haan, Germany) to obtain the pineapple juice used for measurement of TSS. A second sample of flesh was immediately frozen in liquid nitrogen, mixed using a Grindomix blender, and then stored at -80°C until it was used for the determination of flesh dry matter (DM) and soluble sugars.

Data set B included 14 experiments used for estimation of parameters k1 and k2 (used in the model to describe the variation in the parameter k), and for determination of the accuracy of TSS predictions. All fruits were harvested at maturity and weighed (i.e., stages H3 or H4), and TSS were measured. The 14 experiments were carried out in 2006, 2008, 2009, 2010, and 2011 at three locations: Bassin Plat, St Benoit, and Bérive. Bérive is 550 m a.s.l. in the south of the island (55°31'10.59"E, 21°17'10.21"S); the area receives about 900 mm of rainfall per year and has an average temperature of 20.6 °C. In contrast to the other location in the south of the island, there was no possibility of irrigation at Bérive. For studying the effect of management and environmental conditions on the sugar content at harvest, the 14 experiments were aggregated into eight agroclimatic groups according to average annual rainfall (wet or dry), level and kind N fertilization (300 or 150 kg of N ha^{-1}), and the availability of water for irrigation **(Table II. 1)**. The four groups without irrigation were designated wet-300N, wet-150N, dry-NI-300N, and dry-NI-150. The four groups with irrigation were designated dry-I-300N, dry-I-150N, dry-I-0N, and dry-I-150Norg. The pineapples in the first seven groups were fertilized only with mineral N, and the pineapples in the last group were fertilized with mineral and organic N.

2.2. Chemical analysis

TSS were determined with a refractometer ATC-1E (Atago, Tokyo, Japan). A sample of the stored pulp was weighed and then dried at 70 °C for 72 h. The corresponding dry mass was recorded to calculate TSS per unit of pulp dry matter. Another part of the stored pulp sample was used to measure concentrations of soluble sugars. Sucrose, glucose, and fructose contents were measured by high-performance liquid chromatography (HPLC) (Dionex Co., Sunnyvale, CA., USA) (Léchaudel *et al.*, 2005).

Table II. 1. Data sets used for calibration and validation of a pineapple sugar model on? Reunion Island.

Data set		Location	N fertilization (kg N ha^{-1})	Irrigation	Elevation (m)	Year	Annual rainfall (mm)	Agroclimatic group
A	S1,S2	Bassin Plat	300	yes	150	2007/2009	1050/970	-
	E1,E2	Saint Benoit	300	no	290	2008/2009	3830/3616	-
B	D1	Bérive	150	no	550	2010	877	DRY 150N
	D2	Bérive	300	no	550	2010	877	DRY 300N
	D3	Bassin Plat	300	no	150	2012	556	DRY 300N
	S3	Bassin Plat	0	yes	150	2012	556	0N
	S4	Bassin Plat	150	yes	150	2012	556	150N
	S5	Bassin Plat	150	yes	150	2012	556	150N
	S6	Bassin Plat	150 *	yes	150	2011	537	150N+Norg
	S7	Bassin Plat	150 *	yes	150	2010	766	150N+Norg
	S8	Bassin Plat	300	yes	150	2012	556	300N
	S9	Bassin Plat	300	yes	150	2010	766	300N
	S10	Bassin Plat	300	yes	150	2007	1050	300N
	E3	Saint Benoit	300	no	340	2010	4005	WET 300N
	E4	Saint Benoit	300	no	290	2009	3616	WET 300N
	E5	Saint Benoit	150	no	340	2010	4005	WET 150N

*** A legume cover crop was disked into the soil before planting as an organic fertilizer**

2.3. Model description

Fruit were assumed to include two compartments, the peel and the flesh. The flesh compartment represented 72% of the fruit fresh mass (N=20). The flesh water content was equal to the fruit water content simulated by the SIMPIÑA model. The model predicts the daily change in total sugar content in pineapple flesh during the fruit growth period and the TSS at the end of fruit growth, corresponding to harvest at a ripe stage. The simulated period of fruit development corresponds to a period of rapid accumulation of sucrose (Vizzotto *et al.*, 1996), one of the main sugars in pineapple fruit (Py *et al.*, 1984); this period occurs about 6 weeks before harvest (Chen and Paull, 2000) and includes rapid fruit growth and the cessation of growth. The model is based on one proposed for peach by Quilot *et al.* (2004), which is a simplified version of the process-based SUGAR model developed by Genard and Souty (1996) and Génard *et al.* (2003). These models predict changes in TS content in peach flesh over time. Like the previous models (Génard *et al.*, 2003; Quilot *et al.*, 2004), the current model is based on carbon balance in the fruit. The amount of carbon as total sugars in the flesh (CTS) results from the flow of carbon that arrives in the flesh as sugars, via the phloem, in the form of sucrose minus the part of carbon used as substrate for respiration and for the synthesis of carbohydrates other than sugars (e.g., acids, structural carbohydrates, and proteins). Accordingly, the model is defined by the following differential equation:

$$\frac{dCTS(t)}{dt} = \frac{dC_{ph}(t)}{dt} - k(t)\,CTS(t) - \frac{dC_r(t)}{dt} \qquad (1)$$

where t is the time expressed in degree days after flowering (dd), dC_{ph}/dt and dC_r/dt are the phloem and respiration flows of carbon (g dd^{-1}) into and out of the fruit, respectively, and k is the relative rate of consumption of carbon as sugars in the fruit flesh for synthesis of compounds other than sugars (g g^{-1} dd^{-1}).

The model assumes that the phloem flow of carbon is partitioned between flesh growth in terms of dry matter and respiration:

$$\frac{dC_{ph}(t)}{dt} = CC_{flesh}\frac{dDW(t)}{dt} + \frac{dC_r(t)}{dt} \qquad (2)$$

where dDW/dt is the growth rate of the flesh dry weight (g dd^{-1}) and CCflesh is the carbon content of the dry flesh (g g^{-1}). CCflesh is assumed to be constant during the simulated stages of pineapple growth, as demonstrated for other fruits (Genard and Souty, 1996). **Equation 3** was deduced from **Eq. 1** and **2**:

$$\frac{dCTS(t)}{dt} = CC_{flesh}\ \frac{dDW(t)}{dt} - k(t)\ CTS(t) \qquad (3)$$

where CTS (t_{ini})= CTS_{ini} (g) is the initial value.

According to (Grechi *et al.*, 2012), the total sugar content of the fresh flesh at harvest, SS (g g x 10^{-2}), is calculated as:

$$SS(t_h) = 100\ \frac{CTS\ (t_h)}{CC_{sugar}\ (t_h)\ FW\ (t_h)} \qquad (4)$$

where t_h is the day of harvest in degree-days, FW is the flesh fresh weight (g), and CC_{sugar} is the mean carbon content of the sugars (g g^{-1}).

From this calculation of total sugar content at harvest ($SS(t_h)$), the content in TSS (°Brix) at harvest was deduced by an empirical relationship:

$$TSS\ (t_h) = a * SS\ (t_h) + b \qquad (5)$$

2.3. Model inputs

Model inputs consist of daily growth rates of flesh dry weight (dDW/dt) and flesh fresh weight at harvest ($FW(t_h)$). Changes in measured dry weight (DW), fresh weight (FW), and SS from data set A (experiments E1, E2, S1, and S2) were regressed on degree days; a local polynomial function was used. Flesh dry weights and fresh weights determined in experiments in data set B were simulated with the SIMPIÑA model (Dorey *et al.*, 2015). In the SIMPIÑA model, pineapple growth and fruit development in the field and as affected by daily changes in soil N and soil water were simulated. The growth of pineapple is based on radiation interception, conversion to dry biomass, and partitioning of dry biomass into compartments: roots, leaves, stem, peduncle, inflorescence, fruit, crown, and suckers. Fruit demand is calculated as the demand per fruitlet multiplied by the number of fruitlets per fruit. Fruitlet demand is simulated by a potential sigmoidal curve as proposed for other fruits (Léchaudel *et al.*, 2005; Lescourret *et al.*, 1998). Dry matter of each organ was converted to fresh matter by adding a volume of water, which depended on the newly formed dry matter per organ and the specific water content per organ. Fruit water content varied as a function of the sum of degree days (dd) after flowering. Dry matter and fresh matter of fruit were accurately simulated by the SIMPIÑA model, regardless of location, levels of irrigation and fertilization, and planting density (Dorey *et al.*, 2015).

To obtain input data for the eight agroclimatic groups described in Table 1, dry and fresh weights of flesh deduced from the simulated dry and fresh weights of fruits for the 14 experiments were used. The dry and fresh weights of flesh from the various experiments belonging to the same agroclimatic group were regressed on degree-day to obtain a mean daily growth rate (per degree-day) of flesh dry weight and a mean flesh fresh weight at harvest for each group; a local polynomial function was used.

2.4. Estimation of model parameters

Parameters describing the linear empirical relationship between the total soluble solid (TSS) and total sugar content (SS), a and b (Eq. 5), were defined and estimated from data collected at harvest stages (H3 and H4) in experiments of data set A.

Data set A provided inputs that were used to analyze the variation in k, which as noted earlier is the relative rate of consumption of carbon in sugars for synthesis of compounds other than sugars during fruit growth. Based on these observations, an equation was formulated to describe the variation of k. Parameters of the deduced equation for k variation were estimated through sugar model calibration by using nonlinear least squares regression to fit output values of contents in TSS to the observations of TSS from experiments in data set B. For this calibration, CTS_{ini} was derived from an average CTS calculated from the SS measured in pineapple flesh from the first harvest (H1) of data set A, and CC_{flesh} was calculated as the mean of peach CC_{flesh} (Genard and Souty, 1996) and mango CC_{flesh} (Léchaudel *et al.*, 2005), which showed very closed values, because we could not find published values for pineapple CC_{flesh}. CC_{sugar} was calculated at harvest (t_h) for experiments in data set A as the mean value of carbon content (CC_{sugar} i) of the three main sugars analyzed in pineapple flesh (i = glucose, fructose, sucrose), weighted according to the sugar contents of the flesh fresh matter S_i (g g^{-1} x 10^{-2}) (Grechi *et al.*, 2008):

$$CC_{sugar}(t_h) = \sum_{i=1}^{3}(CC_{sugar\,i}(t_h)\ S_i(t_h)) / \sum_{i=1}^{3} S_i(t_h) \quad (6)$$

For this calibration, the sugar model was linked to the SIMPIÑA crop model in order to provide daily growth rates of flesh dry weight (dDW/dt) and flesh fresh weight at harvest ($FW(t_h)$) from experiments in data set B.

2.5. Statistical analysis

Analyses were performed with R software (R Core Team, 2013). The observed means for TSS among agroclimatic groups were compared using Tukey's test with the HSD test R function in the Agricolae package (De Mendiburu, 2009). For the statistical analysis, the null hypothesis of an absence of effect or difference was rejected when the *P*-value was $\leq$ 0.05. The linear and nonlinear least squares methods that were used to fit models were provided by the lm and nls functions of R software, respectively. The local polynomial regression fitting method was provided by the loess function (Chambers and Hastie, 1992).

2.6. Model goodness-of-fit and validation

The goodness of fit of the model was based on the relative root mean squared error (RRMSE) (Kobayashi and Us Salam, 2000), which is commonly used to quantify the mean difference between simulations and measurements:

$$RRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}}{\bar{y}}$$

where y_i is the observed value, $\hat{y}_i$ the corresponding simulated value, N the number of observations, and $\bar{y} = \sum_{i=1}^{N}\frac{y_i}{N}$ the mean of observed values.

2.7. Sensitivity analysis of the model

Sensitivity of the sugar model was analyzed for each model parameter using data from experiment S10. Sensitivity to model parameters was also investigated for TSS at harvest.

3. Results

In fruit harvested close to maturity, i.e., at 1400 degree-days after flowering, TSS content was strongly related ($r^2 = 0.55$, $P<0.001$) to total soluble sugar content in the flesh (**Fig. III. 1**). From this relationship, parameters a and b **(Eq. 5)** were estimated. The total sugar content in the pineapple flesh (SS) increased during fruit growth to the turning stage (H3) and was then stable to ripe stage (H4) **(Fig. III 2A)**. The variation in the relative rate of consumption of carbon in sugars in the fruit flesh for synthesis of compounds other than sugars depended on degree days after flowering and decreased to 0 at the harvest of ripe fruit (**Fig. III. 2B**). Based on these changes, the following equation was chosen to describe the variation of k in the model:

$$k(t) = k_1 e^{(-k_2 \cdot t)} \qquad (8)$$

where t is the sum of degree-days after flowering. Results of the estimation of parameters k_1 and k_2, based on the model resulting from the combination of **Eq. (3)** and **Eq. (8)** are given in **Table III. 2**.

When evaluated with data set B, which was derived from experiments conducted under different climatic conditions and with different levels of N fertilization and irrigation, the model predicted the total soluble solids at harvest with an RRMSE value of 0.04 (**Fig. III.3**). Model output, TSS at harvest, was insensitive to k1 and CTS_{ini}. It was more sensitive to CC_{flesh}, k_2, a, and b, and it was very sensitive to CCs_{ugar} (**Table III. 3**).

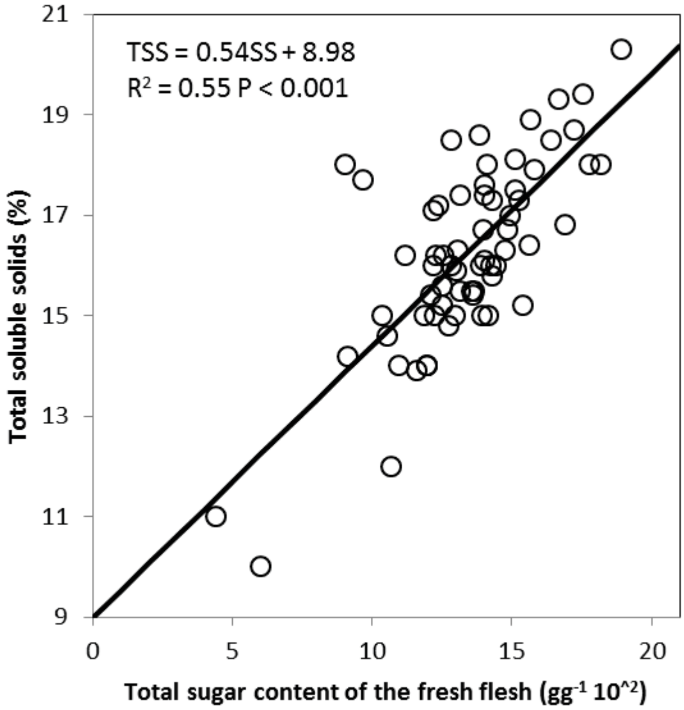

Figure. III 1. Empirical relationship between total soluble solids (%) and total sugar content of the pineapple flesh at harvest

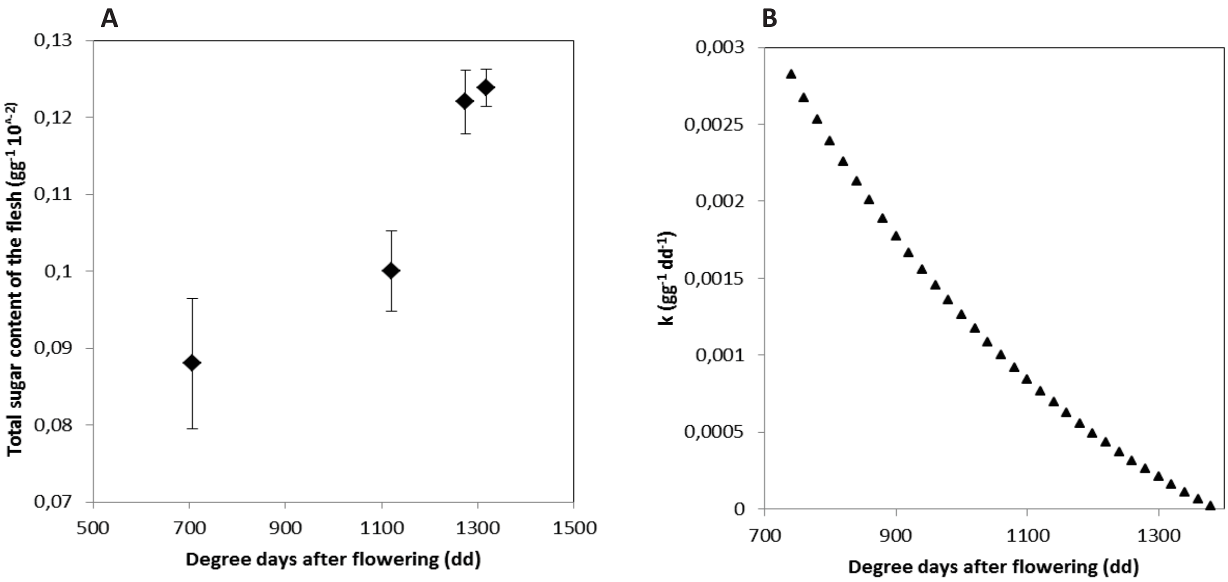

Figure III. 2. Means and standard errors of total sugar content of the pineapple flesh in data set A at developmental stages H1, H2, H3, and H4 (A) and simulated variation in k, which is the relative rate of transformation of carbon as sugar in pineapple flesh for synthesis of compounds other than sugars (B).

Table III. 2. Equations, corresponding parameters, units, and estimated values used in a model that predicts total soluble solids in pineapple fruit at harvest.

Equation		Parameter	Unit	Value	Reference/data sets from this study used for fitting
$\frac{dCTS(t)}{dt} = CC_{flesh} \frac{dDW(t)}{dt} - k(t)\ CTS(t)$	(3)	CC_{flesh}	$g.g^{-1}$	0.4345	(Génard and Souty, 1996; Léchaudel et al., 2005)
$SS(t_h) = 100 \frac{CTS\ (t_h)}{CC_{sugar}\ (t_h)\ FW\ (t_h)}$	(4)	CC_{sugar}	$g.g^{-1}$	0.4161	Data set A
		CTS_{ini}	$g.g^{-1}$	10.54	Data set A
$TSS\ (t_h) = a * SS\ (t_h) + b$	(5)	a	$\%.g.g^{-1}$ x 10^2	0.55	Data set A
		b	%	8.85	Data set A
$k(t) = k_1 e^{(-k_2\ .\ t)}$	(8)	k1	dd^{-1}	0.320	Data set B
		k2	dd	0.008	Data set B

The last column indicates the reference (when the parameter value was taken from the literature) or the data set (see Table 1) when the parameter value was adjusted.

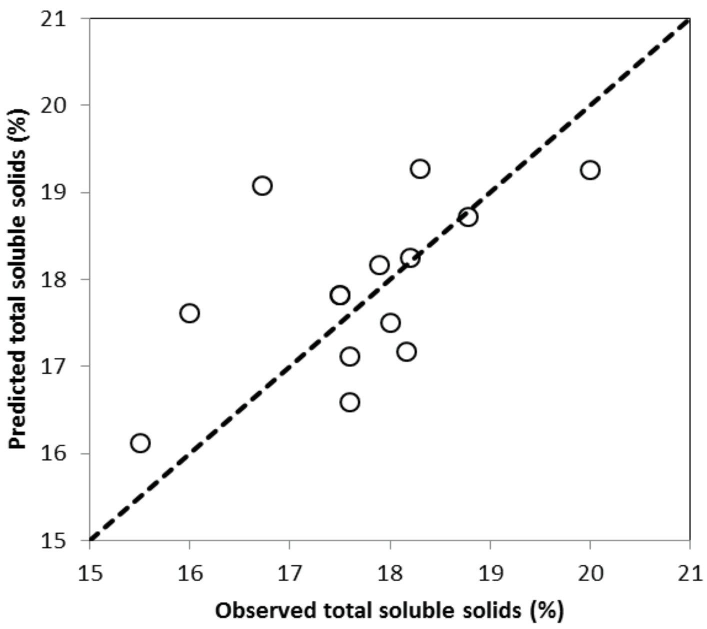

Figure III. 3. Predicted versus observed total soluble solids of pineapple fruit (%) for all experiments in data set 2.

Table II. 3. Sensitivity of fruit TTS to variations (increases or decreases) in model parameters.

Parameter	Extent of variation (%)	Value of deviation (%)
CC_{flesh}	20	-7
	-20	8
CC_{sugar}	20	8
	-20	-16
CTS_{ini}	20	-3
	-20	4
k1	20	1
	-20	-1
k2	20	-2
	-20	10
a	20	-10
	-20	12
b	20	-10
	-20	12

Values are expressed as a percentage of the reference condition. Simulations for the calculation of fruit TTS were performed on fruits from experiment S10.

TSS were highly variable within each agroclimatic group: standard deviations ranged from 0.93 to 1.5 °Brix (**Fig. III. 4**). Values of TSS simulated based on the mean flesh growth within each group were correlated to the observed mean values (r^2= 0.79, y=1.0063x). Observed means for TSS differed among agroclimatic groups. TSS were highest in the dry-NI-300N and dry-NI-150N groups (TSS > 19 °Brix), followed by the dry-I-150Norg group (TSS ~ 18.5 °Brix), and wet-150N, wet-300N, and dry-I-300N groups (TSS ~ 17.5 °Brix). The TSS were < 17 °Brix in the flesh of fruits from the dry-I-150N and dry-I-0N groups (**Fig. III. 4**).

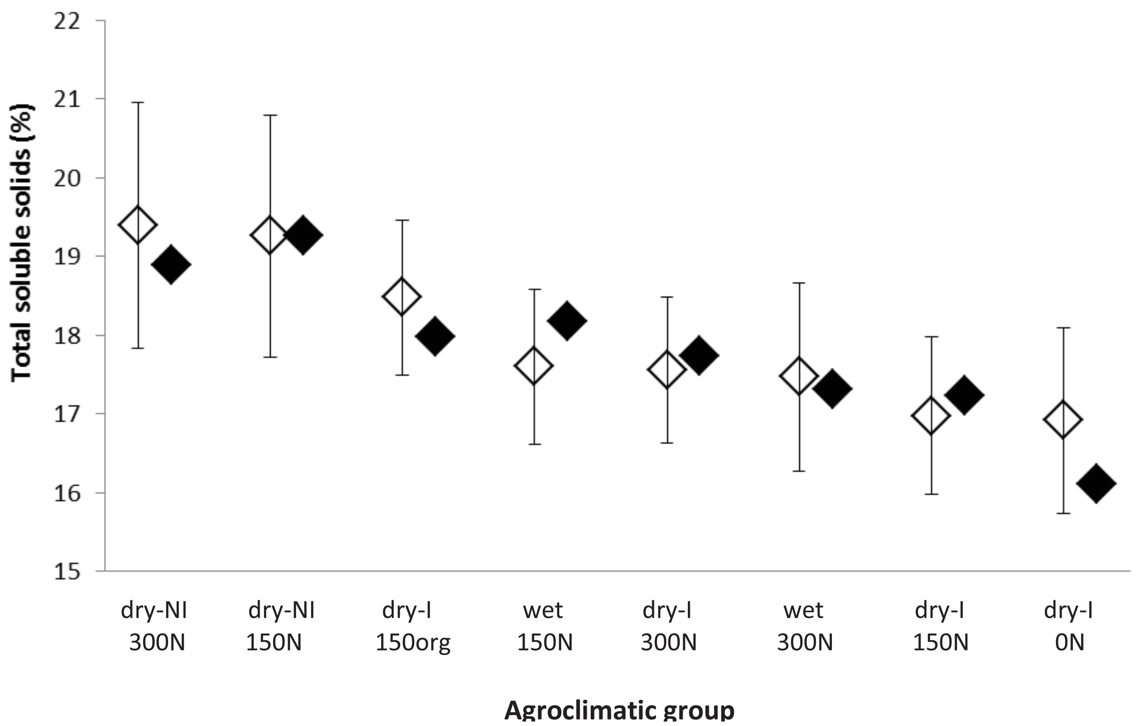

Figure III. 4. Observed values (◊) and simulated values () of total soluble solids (%) in the fresh flesh of pineapple fruit at harvest on Reunion Island for eight agroclimatic groups. Simulated values were generated by a sugar model linked to the SIMPIÑA crop model. Values are means, and standard deviations are indicated for observed data. Observed means with different letters are significantly different at P<0.05 according to Tukey's multiple comparison test.

4. Discussion

The model developed in this study predicted the sugar content of mature pineapple fruit with a level of accuracy (RRMSE = 0.04) sufficient to meet the needs of farmers. This was true even though the pineapples were grown under a wide range of climatic, N fertilization, and irrigation conditions. Because it was linked to the SIMPIÑA crop model, the sugar model developed in this study accounted for the effects of weather (total radiation, temperature, evapotranspiration, and rainfall) and cultural practices (N fertilization and irrigation) as expressed in the growth of fruit flesh. In fact, the efficiency at which light energy was converted into dry biomass was affected by daily changes in soil N and soil water in the SIMPIÑA model. Water content of the fruit was also affected by soil water content because the water that entered the fruit was driven by fruit water content and daily dry matter production. Thus, the simulated increases in the fresh matter of the flesh depended on weather and cultural practices, as reported in many studies on pineapple (Bartholomew *et al.*, 2003; Caetano *et al.*, 2013; De Souza *et al.*, 2009; Py *et al.*, 1984; Zhang *et al.*, 1997; Paula *et al.*, 1991). Sugar content varies throughout fruit development according to the supply of carbohydrates to the fruit, changes in fruit metabolism, and dilution caused by increases in fruit volume (Génard *et al.*, 2003). Environmental conditions and cultural practices influence the water and solute contents in the fruit (Fishman and Genard, 1998). The main physiological processes affecting the sugar content of fruit are the input of assimilates to the fruit and the dilution of sugars in the fruit by water uptake (Guichard et al., 2001). These processes were accounted for in the simulation of growth rates for flesh dry weight and fresh flesh weight by the SIMPIÑA model. The growth rates for flesh dry weight and fresh flesh weight were then used as input for the sugar model.

To confirm the robustness of our model, future research should evaluate the model using data sets generated under other combinations of climate and agricultural practices. It would also be useful to determine levels of specific sugars (i.e., sucrose, glucose, and fructose) in the pineapple flesh because fructose is 2.3-time sweeter than glucose, and sucrose is 1.4-times sweeter than glucose (Kulp *et al.*, 1991). Because gustatory quality also depends on the sugar to acid ratio (Paull and Chen, 2003), it would be useful to develop an acid model. Models of citrate (Lobit *et al.*, 2003) and malate (Lobit *et al.*, 2006) accumulation in fruit have been developed but integrating these models into the current combination of process-based and crop model would require modifications for taken into account the crassulacean metabolism of pineapple.

TSS at harvest depended on flesh growth rate and the effect of metabolic activity in the fruit, i.e., the rate k, which describes the rate at which sugars are consumed and transformed into non-sugars (Lescourret and Genard, 2005). The value of k during fruit development was reported to decrease in several studies (Grechi *et al.*, 2008; Prudent *et al.*, 2011) but was considered constant by Quilot *et al.* (2004). Because the sugar model is driven by changes in flesh dry matter, the greater the growth of flesh dry matter, the more sugar accumulates (Génard *et al.*, 2003). Our results indicate that k should not be treated as a constant, that it decreases as fruit matures, resulting in a substantial accumulation of sugar at the end of pineapple fruit growth (Chen and Paull, 2000). In contrast, a sugar model for peach (Grechi *et al.*, 2008) was not sensitive to k, and the authors inferred that environmental conditions could be neglected for the estimation of k. Although the integration of environmental factors could improve the estimation of the rate at which sugar is transformed into other compounds, it greatly increases model complexity (Génard *et al.*, 2003). The sugar model was not sensitive to variations in CTS_{ini} value, even though the initial accumulation of sugar was based on the initial CTS value.

We hypothesize that sugar accumulation was more closely associated with the increase in fruit dry weight and water accumulation during fruit development than with CTS_{ini}. The model was sensitive to a decrease in CC_{sugar}, similar results were obtained with the sugar model for peach (Grechi *et al.*, 2008). CC_{sugar} represents the mean value in carbon content of the three sugars in pineapple fruit as determined from experimental data.

Sugar content was influenced by environmental conditions and cultural practices. The effect of dilution has only been studied through the effect of irrigation on fruit quality. Sugar content usually decreases in proportion to the water supply (Azevedo *et al.*, 2008; Crisosto *et al.*, 1994; Li *et al.*, 1989). In current study, TSS were highest for the dry-NI-300 and dry-NI-150 groups. The experiments in these groups were conducted in dry locations without the possibility of irrigation. Water is important at most stages of pineapple development, and water stress could be an important cause of yield loss. Pineapples harvested in dry locations, which were smaller and contained less water than pineapples harvested in well-irrigated locations, had high levels of TSS due to a low dilution of compounds accumulated during fruit growth and to an active accumulation of solutes that help fruits cope with water stress (Garcia-Tejero *et al.*, 2010; Morgan, 1984; Yakushiji *et al.*, 1996). Deficit irrigation also increases TSS in peaches (Lopez *et al.*, 2010) and prunes (Intrigliolo and Castel, 2010). Thus, a reduced gustatory quality in pineapple that was attributed to the combined effects of high temperature and excessive rain (Nakasone and Paull, 1998) was simulated by the linking of a pineapple sugar model and crop model in the current study. High rainfall in the cold season 1 month before harvest may reduce the TSS content in pineapple fruit (Bartholomew and Paull, 1986). High rainfall also reduced the concentration of sugars in strawberries (Herrington *et al.*, 2009).

In pineapple fruits grown under well-irrigated conditions and with recommended levels of N fertilization (Fournier, 2011), i.e., 300 kg N·ha^{-1}, gustatory quality was high, with TTS values close to 17.5 °Brix. The agroclimatic group Dry-I-150Norg had TSS values > 18 °Brix. In previous studies, application of manure enhanced the TSS of pineapple fruits (Liu and Liu, 2012), and the application of organic fertilizers in general enhances yield and quality of fruits (Chang *et al.*, 2010; Marzouk and Kassem, 2011; Tejada and Gonzalez, 2003). Pineapple fruits with the smallest TSS value (i.e., < 17 °Brix) in the current study grew under N-deficient conditions with 0 or 150 kg N·ha $^{-1}$, regardless of soil water conditions. These fruits had low weight due to a low dry matter accumulation during fruit growth probably because the deficiency in N caused premature leaf fall and early vine senescence (Okwuowulu, 1995). Fruit water content, however, was not affected; as a consequence, few compounds accumulated and those that did were diluted during fruit growth (Omotoso and Akinridae, 2013). These results once again demonstrate that the sugar model for pineapple, when linked to the SIMPIÑA crop model, accounted for environmental conditions and cultural practices that helped explain the observed variability in gustatory quality of pineapples grown in Reunion Island.

5. Conclusion

We showed that a sugar model for pineapple, when linked to the SIMPIÑA crop model, accurately simulated total soluble solids in fruits grown under a wide range of climatic conditions and cultural practices. The crop model was used to predict the daily change in flesh dry and fresh weight. Output from the crop model was used as input to the sugar model, which was simple and accurately predicted the gustatory quality of pineapple at harvest as affected by agroclimatic conditions. The linking of these two models should help growers manage their pineapple fields and design new pineapple production systems.

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III. B. Effect of climatic conditions on pineapple acidity at harvest

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Abstract

A statistical model to predict pineapple acidity at harvest was developed in order to identify what are the periods (in the flowering – harvest interval) during which each climatic variable (rainfall, global radiation, and temperature) affect most acidity at harvest on Réunion Island. The method used in the study was carried out in two steps: (i) selecting without *a priori* most promising periods of integration of climatic variables between the flowering-harvest intervals, (ii) builting a complete linearized mixed effect model (GLM) based on all candidate variables to predict acidity. Two significant variables were integrated within the early period of growth of pineapple fruits (Temperature1, Rainfall1), while the two significant variables Rainfall 2 and Radiation 1 had an effect at the end of pineapple growth. The complete GLM with the four significant variables and an interaction between Temperature 1 and Rainfall 2 significantly correlated to acidity at harvest explained almost 61% of the variance.

Comparison of observed and predicted data for the 14 experiments demonstrated that the model accurately simulated the acidity at harvest (RRMSE = 0.08). The method developed in this study allowed to highlight the impact of climatic variables and more precisely the sensitive periods of their effects during fruit growth on acidity prediction at harvest. Our model will help farmers to select the date of planting and date of flowering induction in order to optimize TA and better management of pineapple quality on Réunion Island.

Keywords: *Ananas comosus* (L.) Merr., quality, acidity, sugar content, climatic stress

1. Introduction

Fruit taste and quality trait depends on factors as sugar, organic acids, firmness and amino acids. Organic acid plays a crucial role in food nutrition (Silva *et al.*, 2004; Zampini *et al.*, 2008). Acidity is also one of major criterion for organoleptic characteristics of fruits (Bai and Lindhout, 2007; Lobit *et al.*, 2002).In the case of pineapple, the harvest index is determined according to the sugar/acid ratio (Paull and Chen, 2003).Citric and malic acids are the two dominant organic acids in most fruit species (Lobit *et al.*, 2003). In pineapple fruit, citric acid represents 60% and malic acids represent 36% of organic acids (Chan *et al.*, 1973). Variations in acidity during fruit growth is mainly the result of citric acid content variations while malic acid content is relatively constant (Singleton and Gortner, 1965). During pineapple fruit growth, acidity increases until a stage corresponding to a yellow external color for pineapple cultivars that external color changes occurred with ripening and then decreases (Singleton and Gortner, 1965; Smith, 1988b; Teisson and Pineau, 1982). Acidity is the result of complex physiological processes in which respiration plays a great role, i.e. acids are used as metabolites for respiration during pineapple growth and maturation (Wills et al. 1987). This is especially true in the case of pineapple that has a CAM photosynthesis metabolism in which the CO_2 is stored as the four -carbon acid malate during the night and then used for photosynthesis during the day (Cote, 1988). Besides, the final content of acid in pineapple at harvest is thus strongly influenced by climatic factors (Bartholomew and Paull, 1986; Singleton and Gortner, 1965).

Disentangling the effect of climatic variables on acidity is relatively complex since they may alter plant physiological processes at different period of the fruit growth (Marsh *et al.*, 1999). Some studies attempted to link one climatic variable to acidity, e.g. temperature on grapevine (Etienne *et al.*, 2013; Sweetman *et al.*, 2014) and rainfall on nectarines (Thakur and Singh, 2012). However, the period of action of each climatic variable and the duration of the period in which the variable has to be considered is usually poorly documented. The construction of a model that include the effect of the different climatic variables to predict acidity remains needed to help farmers to adapt their periods of production to optimize fruit quality in their area of production.

Pineapple ('Queen Victoria' cultivar) was produced on Réunion Island, which is an island country located in the Indian Ocean, east of Madagascar. It was the first fruit to be produced on the Island. Pineapple is grown under a wide range of conditions on Réunion Island, where the elevation ranges from 50 m to 900 m a.s.l. and annual rainfall ranges from 500 mm to 5000 mm. This diversity of conditions under a relatively managing system makes this production area particularly suitable to study the effect of climatic conditions on titratable acidity. Furthermore, pineapple pests are nearly absent from this area, which limit potential interferences on titratable acidity constitution through stresses of growth. An unusual feature of pineapple production on Réunion Island is that harvest may occur every month of the year because floral induction is controlled by the farmer. It constitutes an interesting option of management for farmer to optimize fruit quality including acidity. It is also an ideal biological model to study the effect of climatic variable on titratable acidity.

In this paper, we use a dataset including 1800 measurements of titratable acidity in pineapples grown in contrasted regions of Réunion Island (i) to identify what are the periods (in the flowering-harvest interval) during which each climatic variable may affect titratable acidity, and ii) to establish a statistical model to predict acidity at harvest. We used an original statistical method to determine the period in which rainfall, global radiation, and temperature affect most acidity at harvest. Then we used the selected period of each climatic variable to build a linear model to predict acidity at harvest.

2. Materiel and methods

2.1. Experimental sites

We measured titratable acidity (TA), which is a common measure of acidity (Lobit et al. 2002), from 14 independents experiments from contrasted climatic zones (from 150 to 550 m a.s.l.) on Réunion Island (**Table III. 1**). Totally, 1448 TA were measured. In all experiments, flowering was induced with ethephon (Ethrel; Bayer SA) at a rate of 3 L ha^{-1} when the plants had reached a weight of 1.2 kg. When irrigation was applied, plots were drip irrigated under plastic mulch. The southwest field received drip irrigation and the water status of the soil were regularly checked with Watermark sensors (Irrometer Company, Riverside, CA), while the east field was not irrigated, given the natural rainfall (**Table III. 1**). Each experiment was managed identically following the locally recommended cultural practices: calibrated suckers (250 g +/- 25 g) were planted on polyethylene mulch and the fields were fertilized with 300 kg ha^{-1} of nitrogen (i.e. 650 kg of urea) and 450 kg ha^{-1} of potassium (i.e. 900 kg of sulfate) or 150 kg ha^{-1} of nitrogen (i.e. 325 kg of urea) and 225 kg ha^{-1} of potassium (i.e. 450 kg of sulfate). Experiments 6 and 7 received 150 kg ha^{-1} of nitrogen (i.e. 325 kg of urea) and 225 kg ha^{-1} of potassium (i.e. 450 kg of sulfate), and a legume cover crop was disked into the soil before planting as an organic fertilizer.

Table III. 1. List of experiments used to analyze the variation in TA at harvest.

Experiments	Location	N Fertilization (kg N ha-1)	Irrigation	Flowering date	Harvest date	Annual rainfall (mm)	Mean of fruit weight at harvest (g)	Mean of TA at harvest
1	Bérive	150	no	07/2010	11/2010	877	597	11,85
2	(55°31'10.59"E,21°17'10.21"S	300	no	07/2010	11/2010	877	606	13,98
3		300	no	08/2012	11/2012	556	492	11,92
4		150	yes	08/2012	11/2012	556	674	11,24
5		150	yes	04/2012	07/2012	556	696	21,41
6	Bassin Plat	150 *	yes	08/2011	11/2011	537	601	11,81
7	(55°29'20.64"E,21°19'21.62"S)	150 *	yes	05/2010	09/2010	766	767	13,38
8		300	yes	05/2010	09/2010	766	810	15,84
9		300	yes	08/2012	11/2012	556	618	10,93
10		300	yes	07/2012	10/2012	766	663	18,43
11		300	yes	08/2007	11/2007	1050	562	11,92
12	Saint Benoit	300	no	09/2011	01/2010	3616	560	12,75
13	(55°42'12.86"E,21°05'53.85"S)	300	no	04/2010	09/2010	4005	936	15,63
14		150	no	04/2010	09/2010	4005	882	13,38

* legumine cover crop was disked into the soil before planting

2.2. Climatic variable measurement

In all experiments, temperature (Temperature), rainfall (Rainfall), and global radiation (Radiation) were recorded with a Campbell Scientific^{TM} meteorological station (Sheperd, UK), which was located beside the plot and at 1 m above the soil surface.

2.3. Fruit sampling

Fruits were harvested at a ripe stage, which occurred about 1318 degree days after flowering, with 9.24°C as basal temperature (Léchaudel et al. 2010). Flowering was defined as 50% of inflorescences on the studied field with at least 1 corolla visible. After every harvest, the fresh mass of every fruit, were measured (**Table III. 1**). Then, the peel tissues of each fruit were excised, pulp tissues were sub-samples. A sample of flesh was mixed using a Grindomix blender (Retsch, Haan, Germany) to prepare a volume of pineapple juice needed for the measurements of TA.

2.4. Determination of titratable acidity

A part of the juice sample from fruits harvested was used to measure its TA. The TA, expressed as milliequivalents of acid per 100 mL of pineapple juice, was measured by titration with a 0.1 N NaOH solution up to a pH 8.1 endpoint, using an automated titrimeter (Schott, Mainz, Germany).

2.5. Statistical analysis

Statistical analyses of the significance of climatic variables on TA were carried out in two steps. After selecting without *a priori* most promising periods of integration of climatic variables between the flowering-harvest intervals, we tested their significance in a linear model.

First, we explored how each variable tends to be correlated to TA. We constituted a matrix containing for each experimental site and each date of harvest, all the possible combinations of integration of climatic variables, i.e. integration periods between all possible times between flowering and harvesting. For been able to compare site at different elevations, we counted this time in degree-days. All combinations were thus defined by a given number of degree-days after flowering and by a given duration in degree-days (cases in which the end of the period of integration exceeded the harvest were eliminated). We established this integration matrix with a 20-degree-day step, leading to 666 possible periods of integration for each climatic variable. For each period of integration, we calculated the mean value of each climatic variable, except for rainfall that was cumulated. Then, we used linearized mixed effect model, lmer function from the lme4 package (Bates *et al.*, 2011) to calculate the Akaike's information criterion (AIC, Akaike, 1973) of each combination of integration of each climatic variable on quality variables, including the experiment as a random term in the model. The graphical representation of AIC values as a function of the beginning and ending of the integration period allowed us to determine which periods (one or two periods according to the variable) of integration better predict quality variables, i.e. with lowest AIC values. This automatized procedure and all statistics were performed with the R software (R Core Team, 2013). At the end of this first step, a list of candidate variables was defined (each candidate variable representing a period of integration for a climatic variable).

In the second step, we built a complete linearized mixed effect model based on all candidate variables to predict acidity with the experiment as a random term in the model. We used a backward model selection process to find the optimal model by eliminating non-significant variables and their interactions (Zuur *et al.*, 2009) using the lme4 package (Bates *et al.*, 2011). We verified the normality of residues of the models (**Fig. S1**). A pseudo correlation coefficient was calculated to assess the part of the variance of data explained by the model (Singer and Willett, 2003; West *et al.*, 2003). The final model was used to predict the effect of climatic variables (in the range observed in our experiments) on TA. Predictions were carried out with the predictSE.mer function from the AICcmodavg package (Mazerolle, 2006)

2.6. Model goodness-of-fit and validation

The goodness of fit of the model was evaluated through the relative root mean squared error (RRMSE) (Kobayashi and Us Salam, 2000), which is a common criterion to quantify the mean difference between simulations and measurements:

$$\mathrm{RRMSE} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}}{\bar{y}}$$

where y_i is the observed value, $\hat{y}_i$ the corresponding simulated value, N the number of observed data, and $\bar{y} = \sum_{i=1}^{N}\frac{y_i}{N}$ the mean of observed values.

3. Results and Discussion

The center of zones with lowest AIC allowed to define the periods of climatic variables that affect most TA (**Fig. III. 1**). Most promising combinations of integration for each climatic variable are summarized in **Table III. 2**. Temperature at 180 degree-days after flowering and during 100 degree-days (Temperature1), Rainfall at 220 degree-days after flowering and during 100 degree-days (Rainfall 1), Rainfall at 600 degree-days after flowering and during 120 degree-days (Rainfall 2), and global radiation at 880 degree-days after flowering and during 120 degree-days (Radiation 1) were significantly correlated to TA. The interaction between Temperature 1 and Rainfall 2 was also significantly correlated to TA.

Table. III 2. Most promising periods of integration of climatic variables to predict TA. Integration periods are defines by their Begin (number of degree-days after flowering) and their Duration (number of degree-days after beginning).

Variable code	Variable	Begin	Duration
R1	Rainfall1	220	100
R2	Rainfall2	600	120
T1	Temperature1	180	100
Rg1	Radiation 1	880	120

The method to select potential climatic variables, i.e., rainfall, radiation, and temperature, during fruit growth to predict pineapple TA at harvest is interesting since it doesn’t have *any a priori* on the period of influence of each variable. While the climate just before harvest is known to impact fruit growth and TA at harvest (Zhang *et al.*, 2011), we showed that key periods selected, which affected TA at harvest, could occur at different stages of pineapple growth. All the possible combinations of integration of climatic variables were defined in degree-days, allowing the association of each combination to a period of growth of pineapple fruit. The aim of the first step of the method we propose here was not to define precisely the effect of climatic variable but rather to identify critical periods of each climatic variable using whole trends on the prediction acidity at harvest. Pinpointing in the center of the areas of influence (with lowest AIC values) of each variable allowed selecting most promising combination. To our knowledge this is the first time that such a method was used to select the effect of climatic variables on a fruit quality attribute. It could probably be used in many other cases to link climatic variables to agricultural and food characteristics.

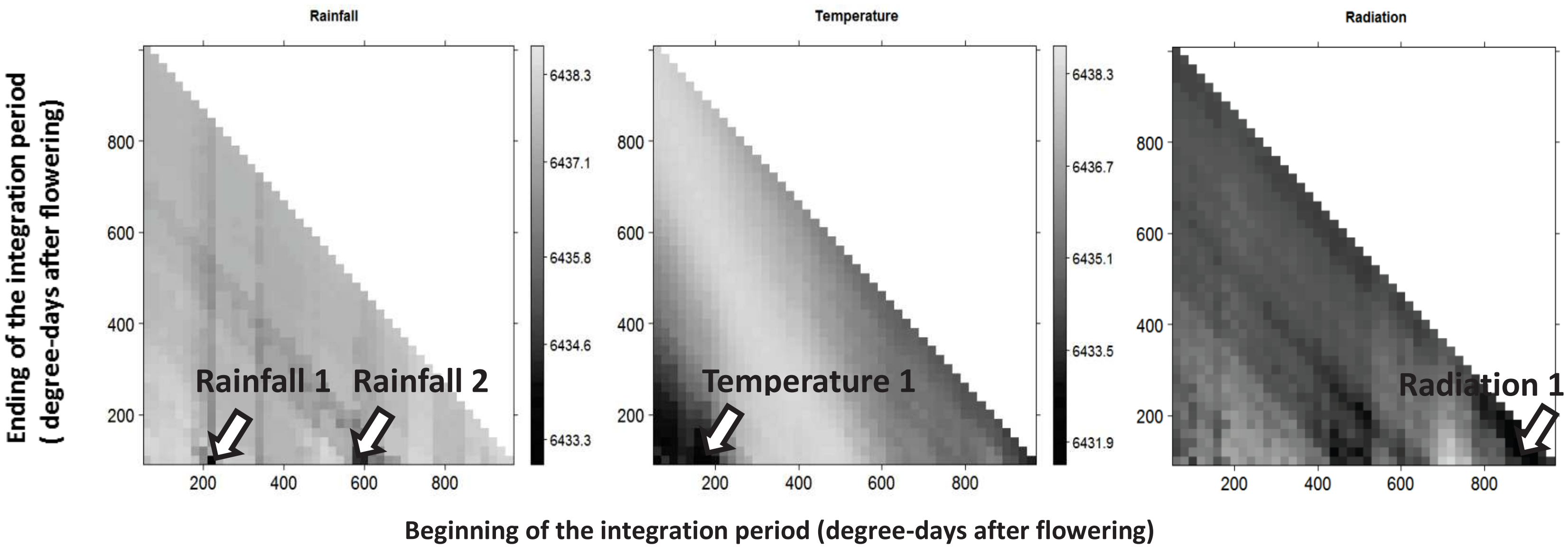

Figure III. 1. Representation of AIC values as a function of the beginning and ending of the integration period for each climatic variable. The arrows represent the lowest values of AIC.

All the four climatic variables selected, all were significantly correlated to TA in the complete GLM (**Tables III. 3 and S1**). The complete GLM with the four significant variables and the interaction explained almost 61% of the variance of TA at harvest (estimated with the pseudo correlation coefficient) (**Table III. 3**).

Table III. 3. Summary of Analysis of Variance (ANOVA) perform on complete model TA = T1 + R1 + R2 + Rg1 + T1:R2 + (1|experiment).

Models	Df	AIC	logLik	deviance	ChisqChi	Df	P
Complete	8	6420.5 -	3202.2	6404.5			
-T1	7	6434.8	3210.4	6420.8	16.355	1	5.e-05
-R1	7	6425.6	-3205.8	6411.6	7.1633	1	0.0074
-R2	7	6432.9	3209.5	6418.9	14.473	1	0.0001
-Rg1	7	6436.9	3211.4	6422.9	18.377	1	1.8e-05
-T1:R2	7	6433.3	3209.6	6419.3	14.818	1	0.00011
NULL	3	6436.3	-3215.2	6430.3	25.87	5	9.455e-05

R1, R2, T1, and Rg1 *for variables Rainfall 1, Rainfall2, Temperature 1, and Radiation 1 (see Table 2 for details)*

Comparison of observed and predicted data for the 14 experiments demonstrated that the model accurately simulated the acidity at harvest (RRMSE = 0.08) (**Fig.III. 2**). Temperature1 and Rainfall 1 had a strong positive effect on TA (estimates equals to 2.69 and 2.53, respectively). The others variables in the model had moderate negative effect on TA, except for Radiation 1 which had an estimate value of -1.75. Predictions with the model within the range of climate of Réunion Island showed the relative weight of the Rainfall 1, Rainfall 2, Temperature1 and Radiation1 on TA (**Fig. III. 3**).

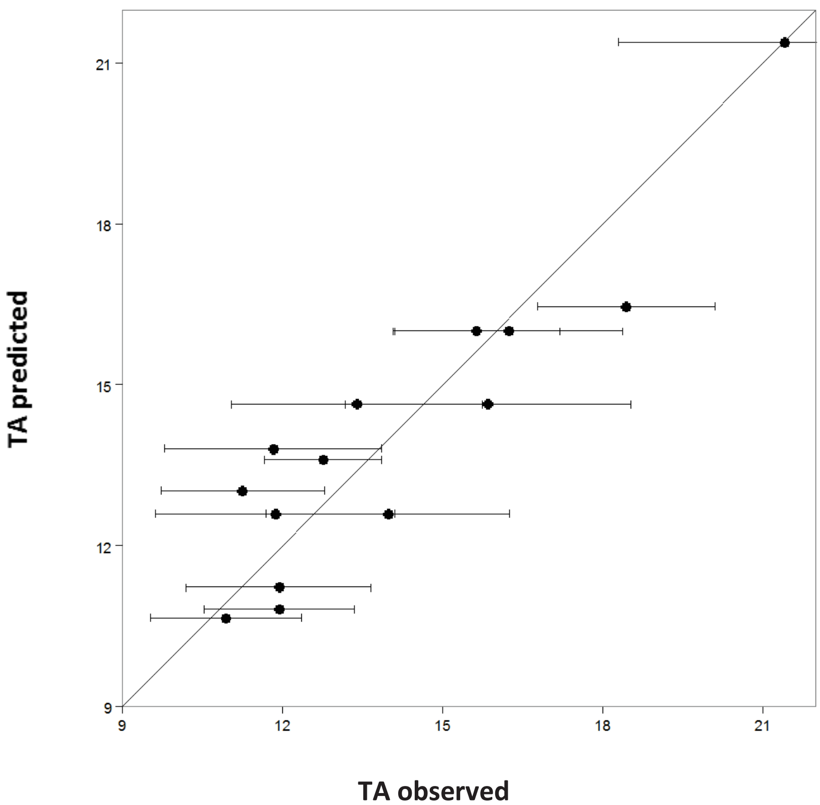

Figure III. 2. Predicted versus observed (+/-standard errors) titratable acidity of pineapple fruit at harvest.

Fruit metabolism depends on stages of fruit growth and strongly influences the biosynthesis or the degradation of compounds involved in quality traits. Moreover, fruit growth determines fruit weight at harvest and also the volume in which compounds were accumulated. Among the significant variables, two were integrated within the early period of growth of pineapple fruits (Temperature1, Rainfall1). These two variables probably affect the establishment of fruit cells during cellular division. The initial fruit size, which is generally related to the cell division is highly correlated to final fruit weight at harvest (Lechaudel et al. 2005). Thus, kiwifruit weight at 50 days after anthesis was reported to explain 75 % of size variations of ripe kiwifruit (Hall *et al.*, 2006).

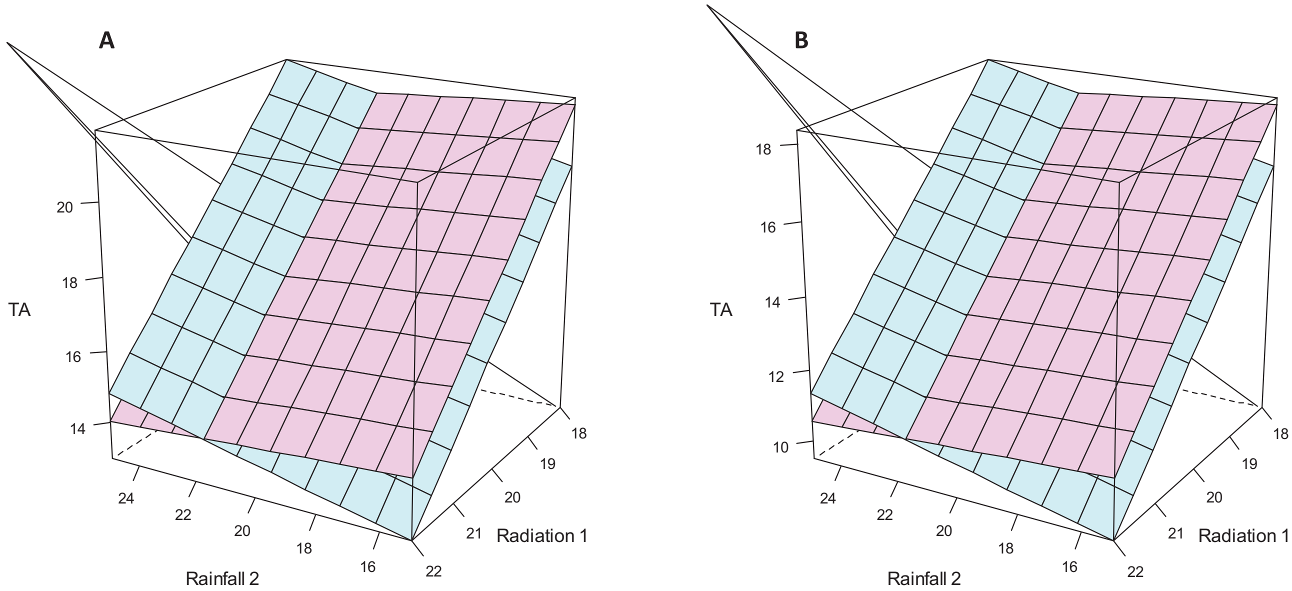

Figure III. 3. Predictions of pineapple TA at harvest from the complete model in relation to periods of climatic variables with Rainfall 1 = 25 (A), Rainfall 1 = 50 (B), Temperature 1 = 19 (blue) and Temperature 1 = 21 (pink).

Fruit growth is generally sensitive to water and carbon supply and to temperature at early stages of growth (Génard *et al.*, 2010). In tomato, lower temperature induced a long period of cellular division leading to an increase of number of cell (Bertin *et al.*, 2006). Experiments 5, 7, 8, 10, 13 and 14 had the biggest fruit's weight and had a growth period in winter leading to high values of TA (**Table III. 1**). Several authors demonstrated high TA in pineapple ripening in winter (Bartholomew, 1994; Collins, 1960; Joomwong, 2006), because of a longest period of fruit development leads to an accumulation of compounds in fruit (Zhang *et al.*, 2011). At low temperatures, synthesis of organic acids was higher than their consumption as substrates for respiration process (Huet and Tisseau, 1959). Conversely, a short period of cellular division was induced when temperatures increased, leading to small pineapple fruits in experiments 3, 4, 6 and 9 **(Table III. 1)** where few compounds of quality may be accumulated, thus showed the smallest TA values.

We showed a negative effect of Rainfall 1 on TA. The variable had a low estimate value. The few studies on the effect of rainfall on pineapple TA at harvest not taken into account early stages of development and were consistency with the effect of Rainfall 2 on TA. Thus, the rainfall at 600 degree-days after flowering and during 120 degree-days (Rainfall 2) was significantly correlated to TA. In pineapple, (Py and Tisseau, 1965) had already demonstrated an increase in TA with excessive water supply.

The global radiation at 880 degree-days after flowering and during 120 degree-days (Radiation 1) was significantly correlated to TA (**Table III. 2**). Our results indicate that fruit harvested from November to February, which is characterized by sunny days, showed the lowest TA values (**Table III. 1**). Usually, variation in fruit acidity was related to period of harvest and several authors demonstrated the importance of global radiation on pineapple acidity which was low when global radiation increased (Combres, 1983; Malezieux, 1991; Malezieux and Lacoeuilhe, 1991). In Ivory Coast, a decrease of global radiation of 66% increased TA of pineapple (Combres, 1979). The positive effect of radiation reduction, by partial shade, on TA was also observed in apple (Schrader *et al.*, 2011) grapevine (Uhlig, 1998) and tomato (Wada *et al.*, 2006).

The global radiation, the main climatic variable related to pineapple acidity (Combres, 1979; Malezieux, 1988; Malezieux and Lacoeuilhe, 1991) was still actively involved in TA prediction but the method developed in this study allowed to highlight the effect of other climatic variables at different stages on TA prediction at harvest. Testing the model with external data would be useful to extend the validity of the model on a broader range of climate, although the 14 experiments used to build the model already cover a large range of seasons and locations where pineapple is grown on Réunion Island. Our model will help farmers to select the date of planting and date of flowering induction in order to optimize TA and better management of pineapple quality on Réunion Island.

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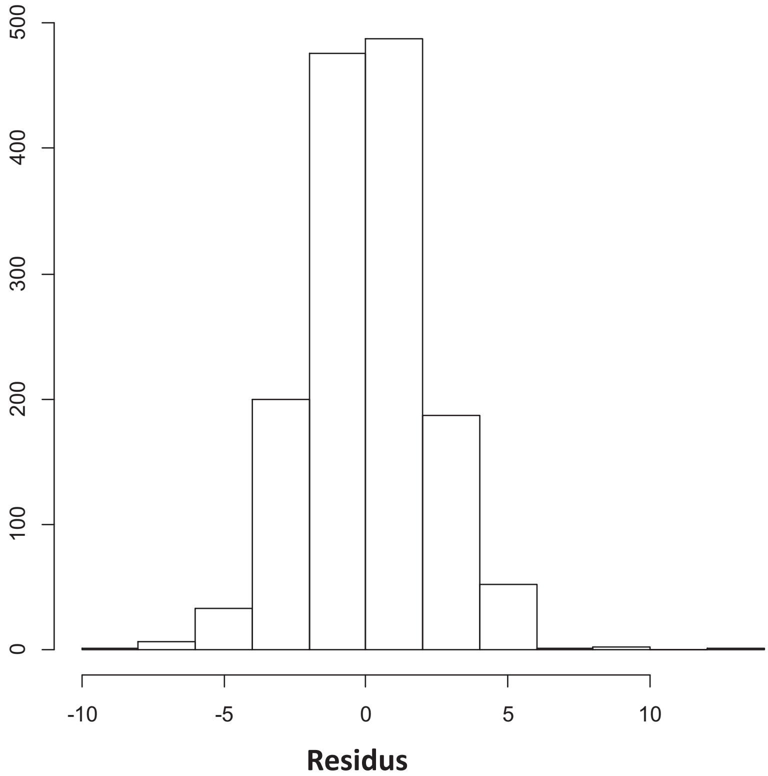

Figure S1. Distribution of the residues and Quantil-Quantil plot of the complete model.

Table S1. Results of the Linear mixed model: TA =T1 + R1 + R2 + Rg1 + T1+ R2 + (1| experiment)

Fixed effects	Estimate	Standard error	t value
Intercept	-0.4012	11.0405	0.036
T1	2.6966	0.6382	4.225
R1	-0.09749	0.0422	-2.309
R2	2.53934	0.66490	3.819
Rg1	-1.75312	0.37524	-4.672
T1:R2	-0.12386	0.0318	-3.893

Chapitre IV – Utilisation de SIMPIÑA pour la conception de systèmes

Ce chapitre repose sur l'article intitulé **'Pineapple cropping system design with the SIMPIÑA modelling framework'**, à soumettre au journal *Agricultural Systems*. Cet article présente l'utilisation du modèle 'SIMPIÑA' qui permet de tester des combinaisons de pratiques en fonction des zones de production de l'ananas à la Réunion, afin d'identifier les systèmes de culture qui optimisent les performances agronomiques, qualitatives, environnementales et économiques des systèmes (**Figure. IV.A**). Un module économique simple a été développé. Une typologie des pratiques culturales a été élaborée afin de réduire le champ des possibles et permettent de proposer des systèmes de culture innovants, en prenant en compte les principales contraintes des exploitations sur la culture d'ananas. L'analyse des systèmes les plus prometteurs s'est faite selon une analyse fréquentielle des pratiques (boxplot) comparée aux pratiques des systèmes actuels. Cela permet à la fois (i) d'identifier les pratiques les plus sensibles dans la capacité de chaque combinaison de pratiques à satisfaire les 4 critères retenus et de (ii) voir la marge de progression par rapport aux systèmes actuels.

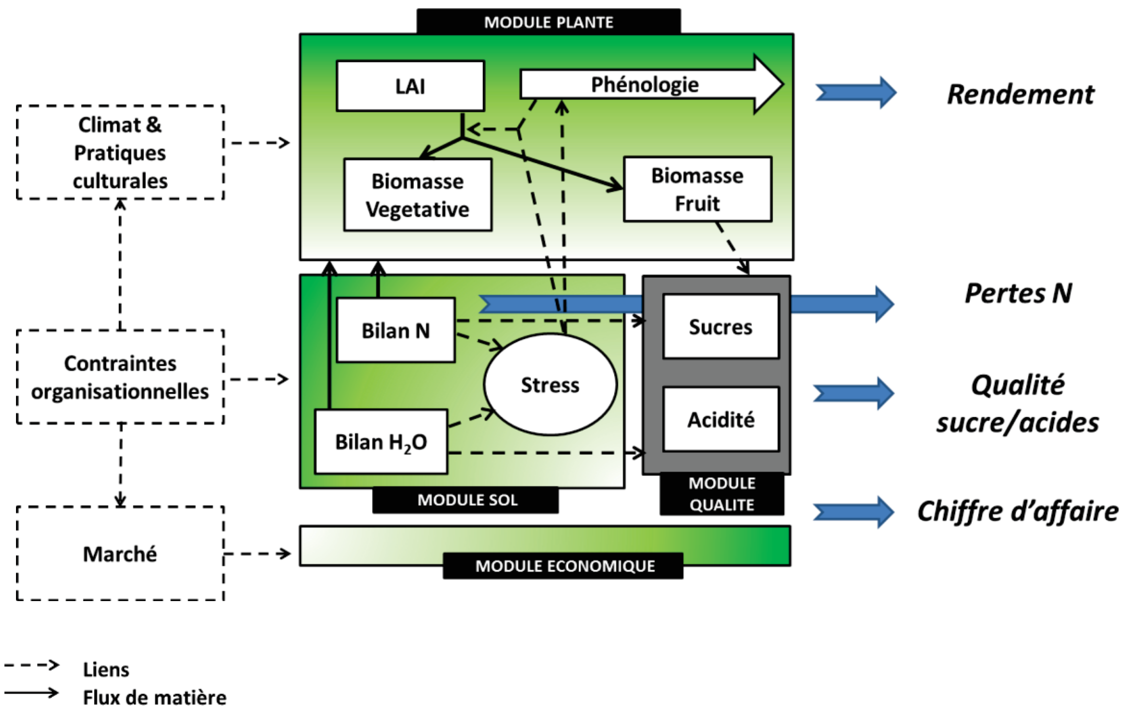

Figure IV. A. Description des modules du modèle SIMPIÑA développé dans le chapitre IV (en vert)

IV.Pineapple cropping system design with the SIMPIÑA modelling framework

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Abstract

Simulation model can be used to assist the design of cropping systems that respond concurrently to environmental, agronomic and socioeconomic constraints. However, most approaches that use models to design cropping system design do not take into account the diversity of farming situations. A typology of farming practices could be used to identify groups with common practices or characteristics in relation to environmental situations and could lead to evaluate the model in contrasted realistic situations. We used the comprehensive SIMPIÑA framework to explore combinations of cultural practices that maximize agronomic, environmental (N leaching), fruit quality (acidity and sugar content), and economical criteria of pineapple systems on Réunion Island. The combinations of cultural practices between three farm-types identified were compared to current systems and discussed on their capacity to improve systems performances according to specific farm constraints.

Keywords: *Ananas comosus* (L.) Merr., Multicriteria evaluation, Typology of farm constraints, Réunion Island

1. Introduction

Nowadays the design of innovative systems is facing many challenges, including environmental issues (limiting the transfer of pesticides and nitrates, reducing emissions of greenhouse gas emissions) while improving the production of food both in terms of quantity and quality (Ahuja et al., 2007). Among the different methods used in the design of cropping systems such as agronomic diagnostic (Doré *et al.*, 1997; Dorel *et al.*, 2008; Loyce and Wery, 2006) and prototyping (Lançon *et al.*, 2007; Rapidel *et al.*, 2006; Vereijken, 1997), the used of process-based model for designing integrated production system is increasingly used, as reviewed by (Ould Sidi and Lescourret, 2011). Using crop model simulations makes possible exploring a very large range of situations (Semenov *et al.*, 2009). Most crop models (e.g., CROPSYST (Stockle *et al.*, 2003), DSSAT (Jones *et al.*, 2003), APSIM (Keating *et al.*, 2003), and STICS (Brisson *et al.*, 1998), are process-based and simulate soil–plant–environment interactions. To improve current systems and allow relevant technical choices, models have to be valid in the domain that needs to be explored (Boote *et al.*, 1996; Cox, 1996). Models can be used at the *senso stricto* conception step (BETHA, Loyce *et al.* (2002a), DECID'Herb, Munier-Jolain *et al.* (2005), SIMBA, Tixier *et al.*(2008)). Models can also be used at the *ex ante* evaluation step, as demonstrated by the farm model BANAD for assessment of agro-ecological innovations in banana farms in Guadeloupe (Blazy *et al.*, 2010).

Multi-criteria assessment of sustainability in innovative cropping system design becomes a prerequisite to increase the usefulness of innovation process (Lançon *et al.*, 2007). Developing more sustainable system by optimizing yield, mineral resources and fruit quality, for both commercial and consumers demand requires methods to perform multi-criteria analyses and to identify trade-offs evaluation criteria. Farming practices have an effect on the cropping system functioning and performances (Meynard *et al.*, 2001). Most approaches that use models to design cropping system do not take into account the diversity of farming situations (Sterk *et al.*, 2007) while the efficiency of innovative systems is dependent of the farming contexts (Orr and Ritchie, 2004) that vary widely among farmers (Bernet *et al.*, 2001). In addition to simulate crop performances in relation to climatic conditions and practices, it is of major importance to take into account the cropping system constraints at both the field and the farm levels in the model-based cropping system design (Vanclay, 2004). A typology of farming practices could be used to identify groups with common practices or characteristics in relation to environmental situations as described by (Blazy *et al.*, 2009). The typology could lead to evaluate the model in contrasted realistic situations as demonstrated by (Colbach *et al.*, 2008) with a typology based on crop rotations to evaluate ALOMYSYS model.

Pineapple ('Queen Victoria' cultivar), the first fruit to be produced on Réunion Island, grown under a large range of climatic conditions, where the elevation ranges from 50 m to 900 m a.s.l. and annual rainfall ranges from 500 mm to 5000 mm. Moreover, according to the location and the farm's structure, a diversity of cultural practices (planting density, level of nitrogen (N) fertilization, irrigation) was observed. The diversity of current pineapple systems leads to various system performances (yield, fruit quality, N leaching). The context of pineapple production on Réunion Island is particularly interesting for the design of innovative cropping system with a process-based model linked to a typology.

In this paper, we present the use of the comprehensive SIMPIÑA modelling framework to simulate combinations of cultural practices that maximize agronomic, environmental (N leaching), fruit quality (acidity and sugar contents), and economical criteria. After defining the typology of climatic and structural constrains of different areas of pineapple production in Réunion Island, we explored combinations of plant management (planting periods, planting density, weight of sucker, date of flowering induction), nitrogen fertilization (level, number of applications) and irrigation practices. We selected systems that lead to the best performances and then defined the trends of cultural practices combinations that satisfy all evaluation criteria. We discuss the sensitivity of each cultural practice in the definition of sustainable systems and the gap between systems selected by the model and current systems for each type identified.

2. Methodology

2.1. The SIMPIÑA model

SIMPIÑA was developed using STELLA® (software environment from High Performance System®, Lebanon, NH). The model runs at daily time-step at the field scale. We used a process-based approach to simulate plant growth, water and nitrogen balances, and sugar accumulation, and a statistic-based approach to predict the acid content of fruits. Finally, an economic module was built with economic farmer's data. The overall SIMPIÑA model allows simulating the pineapple cropping system performances according to climate (temperature, global radiation, rainfall and evapotranspiration) and cultural practices (sucker weight at planting, planting density, level and frequency of N fertilization, irrigation)

2.1.1. Soil and plant growth modules

The description of plant growth and fruit development, affected by daily changes in soil N and soil water was detailed in Dorey *et al.* (2015). Plant growth module was calibrated and tested using data previously collected on Réunion Island under a large range of climatic conditions and cultural practices. Pineapple plant growth and fruit development at the field scale were simulated according to three process-based modules, i.e., plant growth, water balance, and N balance. The growth of pineapple was based on radiation interception, conversion to dry biomass (DM), and partitioning of DM into compartments: roots, leaves, stem, peduncle, inflorescence, fruit, crown, and suckers. After flowering, DM partitioning depended on the demand of each organ. DM of each organ was converted to fresh biomass to simulate pineapple yield. The water balance module simulates soil water content, drainage, and run-off. The soil was considered to be a water reservoir that is increased by rainfall and irrigation and decreased by crop evapotranspiration, drainage and run-off. This module is used to calculate the water stress coefficient that is the ratio between readily available soil content and soil water content. The N balance module was adapted from the model proposed by (Dorel *et al.*, 2008). It simulates at a daily step the mineral N dynamics in soil based on fertilization and soil organic matter mineralization as inputs and crop uptake and leaching as outputs. We considered that only mineral fertilizers are applied. This module is used to calculate the N stress coefficient that is the ratio between N demand and N uptake. Water stress and N stresses coefficients calculated in water and nitrogen balance respectively, altered both pineapple growth and development, in relation to climatic conditions and cultural practices.

Using independent data collected under different weather conditions and planting densities, the model performed well in predicting the vegetative fresh biomass of the pineapple, with RMSE values ranging from 98 to 159 gFM plant^{-1}. Fruit biomass at harvest and date of harvest were also accurately simulated by the SIMPIÑA model over a wide range of weather conditions and planting densities, with RMSE values of 22 gFM fruit^{-1} for fruit biomass and 6 days for date to harvest (Dorey *et al.*, 2015).

2.1.2. Quality modules

We simulate the sugar content of pineapple using a process-based model linked to the plant growth module. It describes the effect of climatic conditions and fruit growth on the sugar content of ‘Queen Victoria’ pineapple at harvest, it is detailed in Dorey *et al.* (2014b). This module is based on carbon balance in the fruit, similarly to Quilot *et al.* (2004) , which is a simplified version of the process-based SUGAR model developed by (Genard and Souty, 1996) and (Génard *et al.*, 2003) . The accumulation of total sugars in the flesh results from the flow of carbon that arrives in the flesh as sugars, minus the part of carbon used as substrate for respiration and for the synthesis of carbohydrates other than sugars (e.g., acids, structural carbohydrates, and proteins). The model assumes that the phloem flow of carbon is partitioned between flesh growth in terms of dry matter and respiration. The ratio of carbon used for synthetizing compounds other than sugars (e.g., acids, structural carbohydrates, and proteins) was estimated during fruit growth. Sugar module inputs are the daily growth rates of dry and fresh matter of the pineapple flesh calculated in the SIMPIÑA plant growth module (Dorey *et al.*, 2015). For data from 14 experiments conducted under different climatic conditions, N fertilization, and irrigation conditions, the model predicted the sugar content at harvest with an RRMSE of 0.04 (Dorey *et al.*, 2014b).

We used a statistical module to predict pineapple acidity at harvest. This module is presented in Dorey *et al.* (2014a). It includes a linearized mixed effect model (GLM) that takes into account climatic variables (rainfall, global radiation, temperature) that were integrated over periods included in the flowering-harvest intervals. This statistical module was built with 1448 data from 14 experiments. There was a good agreement between observed and predicted acidity at harvest (RRMSE = 0.08).

2.1.3. Economic module

The economic module simulates the farmer's revenue. Fruit weights at harvest were partitioned into 3 classes: <500g, 500 -1000g, and > 1000g. The classes determine targeted market (local, export, transformation) in relation to period of harvest (**Table IV.1**). Selling price is a major criterion of economical outputs and is assessing in relation to targeted market and to fruit weight at harvest for local market (**Table IV.2**). Fruit weight at harvest, months of harvest and number of fruit by field, the inputs of economic module, were simulated by SIMPIÑA. Farmer's revenue (FR) was deduced as follow:

$$FR = (VOL_{export.}\ SP_{export}) + (VOL_{transformation.}\ SP_{transformation}) + (VOL_{local.}\ SP_{local}), \qquad (1)$$

with VOL_j, the amount of fruit sold (kg), and SP_j, the selling price, (€ kg-1), of the market j

Fruit weight at harvest	December - March - April			October - November - January - February			May - June - July - August - September		
	Export	Transformation	Local	Export	Transformation	Local	Export	Transformation	Local
< 500g	0%	0%	100%	0%	0%	100%	10%	0%	90%
500 - 1000 g	80%	10%	10%	50%	30%	20%	100%	0%	0%
> 1000 g	0%	90%	10%	0%	100%	0%	10%	90%	0%

Table IV. 1. Percentage of repartition of fruits according to the fruit weight at harvest, the months of harvest and the targeted marketing (export, transformation, and local) (from Pissonnier, 2014).

Targeted market	Farmer's revenue (€ kg^{-1})
Export	1,2
Transformation	0,8
Local	
<600g	0,5
600 - 900g	0,8
> 900 g	1

Table IV.2. Farmer's revenue (€ kg^{-1}) in relation to targeted markets. (from Pissonnier, 2014).

2.2. Typology of farmer's practices

We established a typology of practices using the method proposed by Girard *et al.* (2001; 2008) and adapted by Michels *et al.* (2009) where the definition of types is based on expert knowledge and survey. This typology takes into account both structural and environmental constraints. It was established using data from a survey performed in 2013 in 39 farms representative of pineapple production in Réunion Island. The survey was performed using a semi-directive interview guidelines allowing to collected data on (1) the identification of farms (climatic conditions, locations) and description of activities into the farm, (2) the global farm functioning and (3) the pineapple management system. During a meeting, farm advisor, researchers and farmers defined relevant attributes used to constitute groups with common practices. Each attribute was then represented on an axis opposing two extreme practices, and with intermediate values along the axis. Eleven criteria (**Table 3**) were used to establish the typology. A multiple correspondence analysis ('ade 4' package, Dray and Dufour, 2007) and then a descendant hierarchical cluster analysis ('cluster' package , Maechler *et al.*, 2014) allowed identifying homogeneous groups of farms with similar practices.

2.3. Method to generate and assess cropping system

SIMPIÑA was used to explore a wide range of practices combination in order to analyze the performances of systems simulated. The range of combination practices tested was defined according to the constraints identified for each groups defined with the typology. For each group, we used a climate representative of the production zone (daily values averaged over the 5 years). Each combination of practices was evaluated for its:

- Agronomic performance: yield calculated as the fruit weight divided by the cycle duration,
- Fruit quality performance: ratio between sugar content and acidity at harvest. This ratio is a good evaluation of gustatory quality of pineapple fruit that depends on both sugar and acid ratio (Paull and Chen, 2003),
- Environmental performance: value of N leaching variable calculated in nitrogen balance,
- Economic performance: the farmer's revenue divided by the cycle duration.

Table 3. Description of criterion used for typology.

Category		Criterion	Extreme practices
Field set up	1	Ridges	- Elevated ridges to prevent diseases, erosion, and to facilitate rooting - No ridges
Field set up	2	Tillage	- Important tillage for loosing and prevent erosion - No tillage beacuse of not nescessary or short time to invest
Crop management	3	Planting density	- High planting density - Low planting density
Crop management	4	Level of N	- Level of N > 300 U - Level of N < 300 U
Crop management	5	Number of N applications	- Number of N applications > 8 - Number of N applications < 8
Crop management planning	6	Production's period	- Production throughout the year to ensure regular income - Production in low seasons to have the great selling prices
Crop management planning	7	Access to irrigation	- No irrigation as in humid location - No irrigation in dry location whithout water access

Crop management planning	8	Elevation	- High elevation - Low elevation
Crop management planning	9	Diversification	- Monoculture as in high altitude and financially interesting - Diversification to ensure regular income throughout the year
Field set up	10	Weather	- Mostly humid - Mostly dry
Field set up	11	Location	- North - West

Current systems were simulated with SIMPIÑA model to evaluate performances for each farm-type identified. In order to define trends of systems that satisfy high performances for the four criteria, we first selected combination of practices that overtake a threshold for the four criteria of evaluation. The threshold was defined as the mean of performances for each farm-type. Then, we analyzed the distribution of simulated values of practices included the 10% best evaluation for most promising systems for each type and compared them to the ranges of practices of current systems. A general description of model was presented in **Figure IV.1.**:

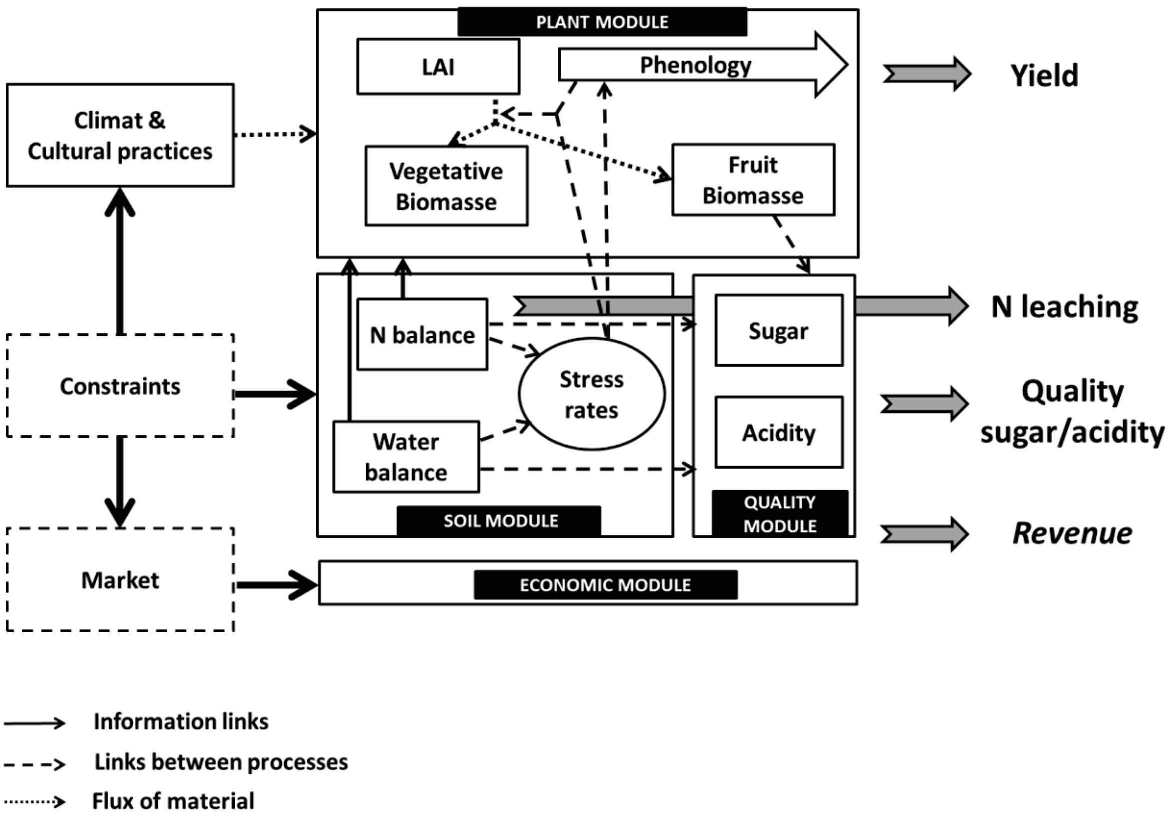

Figure IV.1. General description of the SIMPIÑA model.

3. Results

3.1. Typology of practices and associated farm constraints

Following the typology method, three homogeneous groups were identified: (A) sugar cane farmers located at humid locations, (B) traditional pineapple farmers located at high elevation and (C) diversified farmer with intensive practices at low elevation. The strategy and typical practices of each group are described in **Table IV.4**. For each group the climatic and structural constraints were taken into account in the possible range of practices explored with the model (**Table IV.5**). We can notice that the main criteria which defined the three groups was the location on Réunion Island, and the associated climatic condition (**Figure IV.2**).

Table IV. 4. Description of typical practices for each type

Types	**Typical practices**
A. Sugar cane farmers located at humid locations	- The main production in the farm is the sugar cane - Harvest periods occurs throughout the year planting periods - Planting periods limited to the beginning of the year due to the management of sugar cane the latest six months of the year - Heavy tillage for prevent erosion, diseases, due to the localization in humid area - N Fertilization in the recommended range - Low elevation leads to short-season of production - Low planting density
B. Traditional pineapple farmers located at high locations	- Pineapple crop is the only crop in the farm because of impossibility to produce others crop at high elevations - Located in traditional location of pineapple production - Harvest periods in peak season (at the end of December and in April) - Unfavorable environmental conditions (dry location without possibility of irrigation)

	- Superficial tillage with erosion risks - High elevation results in long-season of production and possibility of natural flowering - High planting density
C. Diversified farmer with intensive practices at low elevation	- Presence of other crops than pineapple in the farm - Harvest periods occurs throughout the year despite presence of others crop in the farm - Favorable environmental conditions (dry location with possibility of irrigation) and low elevation which results in short-season of production - Superficial tillage - Intensive fertilization practices (high N level and high number of N application)

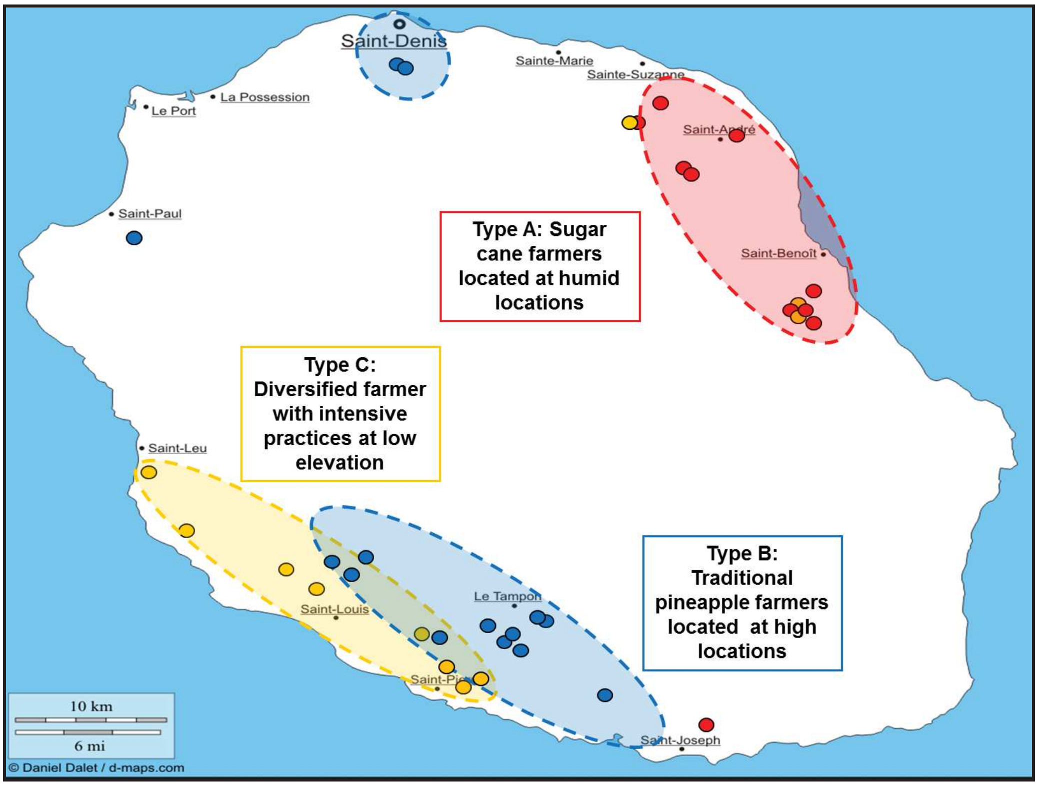

Figure IV.2. Localization of farms and types associated.

Table 5. Combination of practices simulated for each groups after identifying constraints with the typology.

Practice	Type A	Type B	Type C
Planting months*	1, 2, 3	1 to 12	1 to 12
Planting density	from 50 000 plants ha^{-1} to 100 000, every 10 000 plants ha^{-1}		
Flowering induction	from 150 days after planting to 300 days after planting, every 30 days		
Number of N aplication	1, 4 and 8		
Level of N	from 0 to 400 kgN ha^{-1}, every 50 kgN ha-1		
Sucker's weight	from 200 to 400g, every 100g		
Irrigation	no	no	Yes
Number of simulations	8748	34992	69984

* The number used corresponds to the months of year, e. g., from 1 to 12, for January to December, respectively

3.2. Model-based exploration of pineapple systems

We explored 8748, 34992 and 69984 systems for type A, B and C, respectively (**Table IV.5**). The selected thresholds for each farm type are presented in **Figure IV.3**. We selected 81, 77, and 101 systems that satisfy all criteria for the type A, B and C, respectively. The practices associated to the current and selected systems for the three farm-types, except irrigation practices which concerned only type C, are presented in **Figure IV.4.**

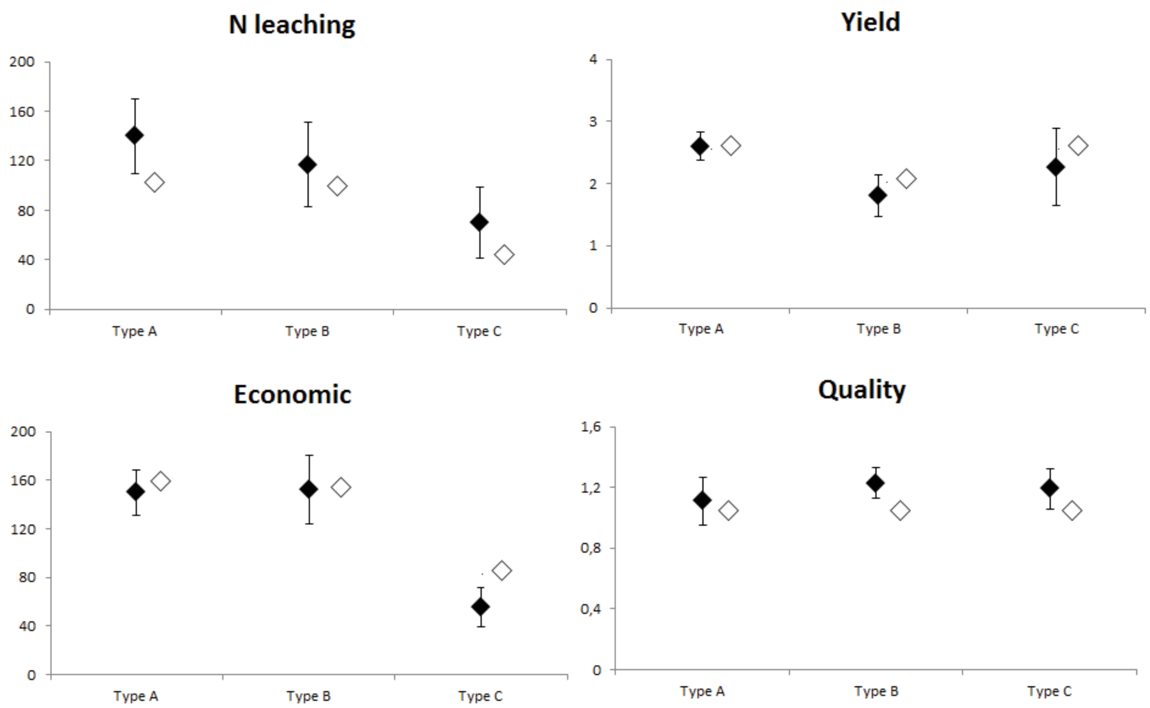

Figure IV.3. Mean (+/- standard error) of system performances, for actual system (black) and simulated system (white) for each type.

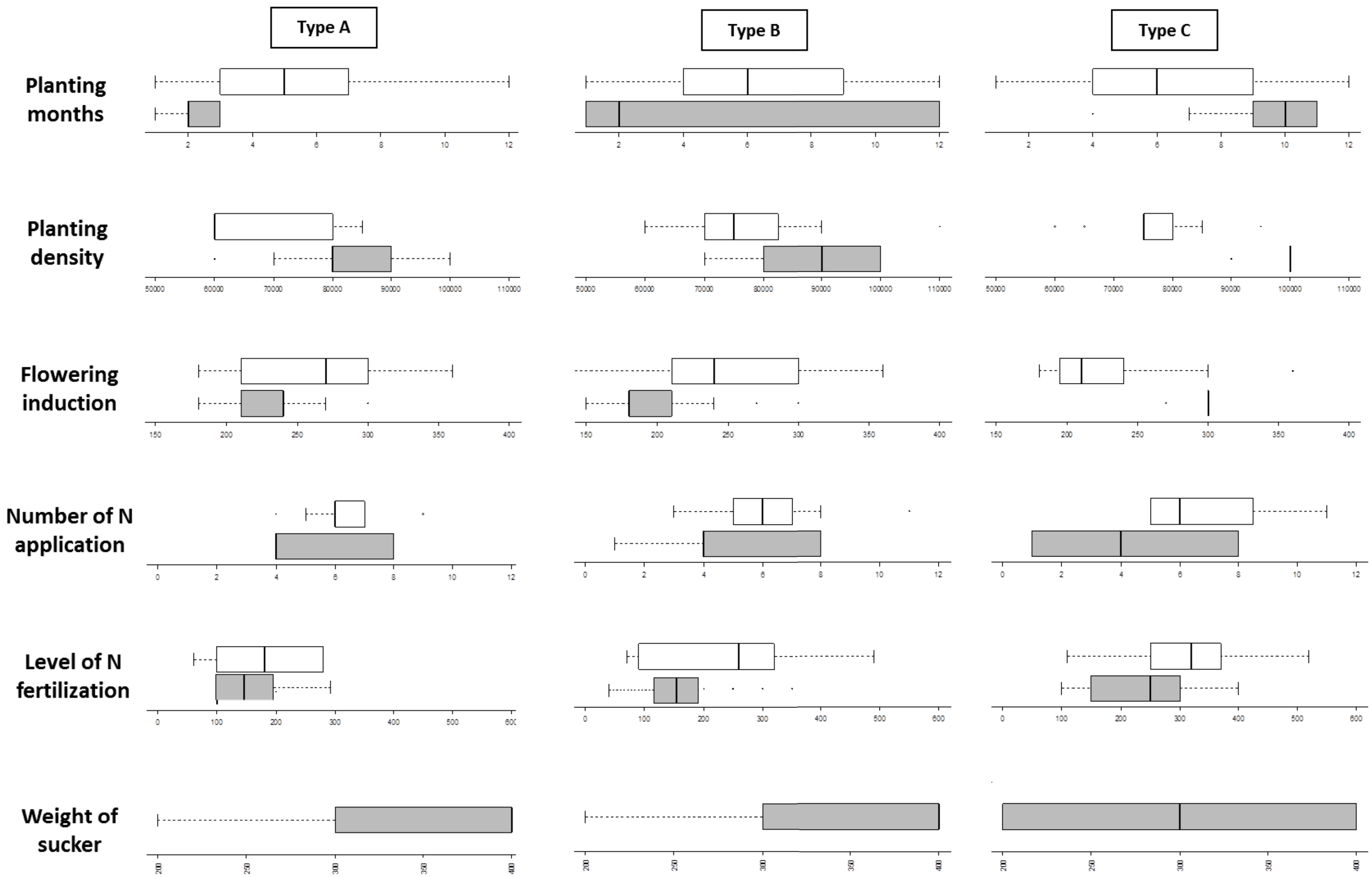

Figure 3. Representation of range of practices for actual pineapple system (white) and selected system (grey).

4. Discussion

Promising systems selected varied according to the farm-types identified. In farm-types A and B, systems selected showed earlier dates of flowering induction than current systems and N fertilization < 200 kg ha^{-1} .By opposite, in farm-type C, date of flowering selected was later than current systems and the level of N fertilization is extend to 300 kg ha^{-1} compared to farm-types A and B but still inferior than current ones. At the opposite, there were some similarities between farm-types, e.g. most promising systems showed high performances with lower of N application. Our results suggest that in most cases, the level of N fertilization can probably be decreased in order to decrease N leaching while maintaining high yield. This is consistent with other studies that showed that yield may be not affected when the N level was reduced from 385 to 215 kg ha^{-1} whereas N surplus was diminished (Grignani *et al.*, 2007). For the three farm-types, planting density was generally higher in the selected systems (with values > 80 000 plants ha^{-1}) than in current ones. High sucker's weight also seems to improve performances of promising systems. It's consistent with the fact that more biomass will be produced with high initial leaf area, so with a high sucker's weight.

Farm-type A « Sugar cane farmers located in humid locations » had specific constraints associated to labor organization especially during the sugar cane harvest (July to December). Cultural practices as calibration of sucker, planting and N fertilization (which occur during plantation to induction flowering interval) were not mechanized and required time and labor which leads farmers to plant pineapples only during the beginning of the year. With a flowering induction earlier than current systems, these farmers could only need one or two N fertilizations applications during the sugar cane harvesting season.

Surprisingly, the same trend was observed for farm-type B "Traditional pineapple producers located in high elevations", with an earlier flowering induction in systems selected compare to actual practices. These farmers were called "traditional" because for these farmers, pineapple is their main crop whereas pineapple is rather now considered as a crop of diversification (Hoarau and Huet, 2004). Farms were located at high elevation where only pineapple can grow (i.e; too high for sugar cane and usually impossibility to irrigate) leading to a long duration of crop development. The weight of plant at flowering induction is well correlated to the number of fruitlets (Dorey *et al.*, 2015; Malezieux, 1988) and to the weight of fruit. Thus, inducing flowering at about 200 days after planting seems to be too early to obtain big fruit enough to get a high yield. Farmers of type B currently harvest pineapple on peak season (December and April) associated to a restricted period of planting whereas promising systems selected suggest that the planting period (and so harvest period) can be extended throughout the year. For farmers of type B the main trend to improve their systems is most probably in extending the production throughout the year and selling smaller fruits (below 500g) to the local market which represents about 86 % of sales. However, at the end of the year, the local market could be saturated because of harvest season of others tropical fruit as, litchi and mango occurred.

For farmers in type C "Intensive diversified producers located in low elevations", there were great differences between current practices and promising systems selected with the model, suggesting a great potential of improvement. Flowering induction seems to maximize systems performances with only one period selected (300 days after planting) which occurs later than the current practice. We can hypothesize that these higher performances with later flowering induction lies in the high yield reached in this case. Indeed, fruit growth initiated in winter leads to big and optimal quality fruits (because they are harvested in warm season. Although farmers of type C could harvest all over the year due to favorable climatic conditions and access to irrigation, it would be interesting for them to plant at the end of the year to target an harvest during the peak season in December. This harvesting peak occurs during the high selling price periods (export market) and is economically advantageous to maximize the gross margin. We can notice that levels of N fertilizers applied was superior both in current systems and promising systems for type C compared to farm-type A and B. Low N leaching is probably possible in these conditions, even with a fertilization of 300 kg N ha^{-1} (maximal value we tested), because farmers of type C are located in dry zone with soil water content rarely saturated. Promising systems that satisfy all criteria for type C were irrigated, confirming that water plays a major role in pineapple growth (Combres, 1983; Malezieux, 1988; Py, 1960).

Promising pineapple systems were selected by considering the multiple effects of cultural practices on productivity, economy, environmental and fruit quality. Various crop models were used to optimize technical scenarios on various performances as yield, mineral resources, environmental risk or gross margin (Arora *et al.*, 2007; Bergez *et al.*, 2004; Debaeke, 2004; Rinaldi and Ubaldo, 2007; Tixier *et al.*, 2008). Although the cultural techniques that control processes involved in fruit quality were studied extensively (Génard and Lescourret, 2004), quality is not taken into account in most crop models. The BETHA model, which simulates and compares specified wheat based cropping systems on the basis of multi-criteria analysis included seed quality to others criteria as yield, cost, gross margin, nitrogen use, pesticide use and energy balance (Loyce *et al.*, 2002b), represents an unusual case of using quality in crop model. Our multicriteria approach could be perform with a non-totally compensatory method based on agreement and discordance principles because criteria may be very different and cannot be directly aggregated as used in the BETHA model.

For the moment, the model probably under evaluated the risks associated to practices which require additional labor's cost as sucker calibration or planting at high density. In future studies, a more elaborated economic module should be developed to make the evaluation of gross margin possible. Economic performance with gross margin indicator are pertinent for designing sustainable systems as proposed by Nelson *et al.* (1998) where the cost of alternative systems was similar to current ones. In our case, environmental performances of pineapple systems could be performed with a relatively simple criterion (N leaching) since no pesticides are used and erosion is limited by plastic mulch. To fit the conditions of other pineapple growing regions more criteria should be taken into account and integrated, e.g. indicators of soil fertility and erosion (Dogliotti *et al.*, 2004) and water exposure to pesticides (Tixier *et al.*, 2008).

To assist cropping system design, crop model must i) have inputs and outputs data defined in relation with the study's objective, ii) valid under climatic conditions and context where it will be used and iii) have a capacity to selected pertinent technical choices (Boote *et al.*, 1996; Cox, 1996; Meynard *et al.*, 2001). The SIMPIÑA model accurately simulates pineapple growth and development across a substantial climatic gradient and thus allows exploring combinations of cultural practices under a diversity of conditions in order to optimize N and water resources while ensuring suitable yield and fruit quality of pineapple on Réunion Island (Dorey *et al.*, 2015). In model-based design, the lack of evaluation of most promising combinations of cultural is always an issue (Blazy *et al.*, 2009). In our case, we did not tested real innovations but rather search optimal cultural practices combinations. The lack of evaluation of most promising systems is thus probably less important.

The method used for selecting promising system is interesting because it did not generate a single solution, but range of combination of practices. According to Grechi *et al.* (2012), this variability within practices selected highlighted that farmers could identify management recommendation which match with their objectives and strategic choices. We believe that our modelling framework could be used in dialogue with farmers as a strategic thinking tool to help them to choose the most relevant system in their own economic, social, climatic situation (Dogliotti *et al.*, 2005). The method developed by Meylan *et al.* (2013) that use a typology to adapt a conceptual model to support the design of coffee-based agroforestry systems, constituted an interesting perspective of use of our model in a participative way. Globally, linking a participatory approach to simulation modelling improve the decision making of farmers (McCown *et al.*, 1996).

The SIMPIÑA model allowed to explore combinations of cultural practices, e.g., irrigation, fertilization, suckers' weight at planting, planting density and period of planting and flowering induction, under a diversity of conditions in order to optimize N and water resources while ensuring suitable yield and quality. The precision of processes included in the model seems to be acceptable for application purposes in crop system design (Boote *et al.*, 1996). The typology led to use the model in contrasted realistic situations, similarly to (Colbach *et al.*, 2008) that used a typology based on crop rotations to evaluate the vulpine infestation with the ALOMYSIS model in contrasted rotations. Our study showed that farmers could improve environmental performance while maintaining a high level of productivity and fruit quality according to their biophysical and technical current situations.

5. Conclusion

In this study, we demonstrated that a dynamic crop model which takes into account the key biophysical processes evaluated with a multi-criteria analyses associated with a typology of practices provide a useful framework for the design of innovative pineapple systems. It will be necessary for further researches to confront innovative systems selected with stakeholders in order to (1) discuss on aptitude of tool to perform relevant choice on system selected and (2) identify farmer's constraints in *ex ante* study to the adoption of innovation.

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Chapitre V. Discussion Générale

1. Acquis, limites et perspectives

L’objectif principal du travail était de rechercher, pour les différentes conditions de production de l’ananas ‘Victoria’ à la Réunion, les pratiques culturales permettant d’améliorer la durabilité et les performances du système de culture. Nous avons donc choisi de construire un modèle, SIMPIÑA, capable de prendre en compte les processus qui affectent le rendement, les composantes de la qualité (teneur en sucres et en acides), et des critères environnementaux et économiques des systèmes produisant l’ananas ‘Victoria’ à la Réunion. *In fine*, le modèle ainsi construit a permis d’identifier les marges de manœuvre des producteurs d’ananas, en fonction des principales contraintes de leurs exploitations et de proposer des tendances d’évolution des systèmes de culture.

1.1. SIMPIÑA, un outil qui intègre des connaissances agronomiques, écophysiologiques et statistiques.

1.1.1. L’effet des pratiques et du climat sur l’élaboration du rendement

Face à l’hétérogénéité des conditions climatiques et des pratiques culturales, la culture de l’ananas à la Réunion montre une forte variabilité en termes de rendement et de qualité gustative des fruits ainsi que dans l’utilisation des ressources naturelles du milieu. Différents travaux de modélisation avaient été entrepris auparavant afin de prédire les différents stades de développement en fonction de l’accumulation du temps thermique (Fleisch and Bartholomew, 1987), puis de simuler la croissance, le développement et le rendement du cultivar ‘Cayenne Lisse‘ au sein d’un modèle dynamique, le modèle ALOHA-Pineapple (Malezieux *et al.*, 1994; Zhang, 1992; Zhang *et al.*, 1997). Cependant, ces modèles ont été calibrés dans des zones à faible variabilité climatique, sans tester de scenarios faibles en intrants, et ils n’ont pas été construits dans une démarche de conception de systèmes de culture. Il nous a donc paru essentiel de construire un nouveau modèle adapté à la variété ‘Victoria’ dans les conditions de productions réunionnaises, qui offrent une large gamme de conditions climatiques, essentielles pour calibrer et évaluer le modèle. Un des atouts de ce travail a été de pouvoir confronter le modèle avec une base de données existante, comprenant de nombreux essais effectués en station expérimentale, au CIRAD de St Pierre à la Réunion, ainsi que des mesures effectuées chez les producteurs dans la majorité des lieux de production de l'ananas sur l'île. Ces expérimentations nous renseignent sur la croissance des plants et la qualité des fruits en fonction de (i) différentes doses de fertilisation azotée et d'irrigation, (ii) avec des densités de plantation et des poids de rejets plantés variés, (iii) sous une large gamme de conditions climatiques, impliquant (iv) des dates de plantation et d'induction florale différentes.

La première étape de ce travail de modélisation a été axée sur le développement d'un module biophysique de croissance de la plante et de développement du fruit, en lien avec les modules de bilans hydrique et azoté. La croissance en matière fraîche de la plante a été simulée en 3 étapes : (i) estimation de la production de matière sèche par les feuilles, (ii) répartition de la matière produite entre les différents organes en croissance en fonction des stades phénologiques considérés, (iii) augmentation du contenu hydrique de chacun des organes. Chaque organe a donc sa propre croissance au sein du module, avec des pourcentages d'allocation de la matière produite en fonction des stades phénologiques spécifiques à chacun. La croissance en matière sèche du fruit dépend, quant à elle, des relations source – puit. La demande du fruit a été modélisée comme le produit de la demande potentielle d'un œil (l'ananas étant un fruit syncarpique composé de sous entités, les yeux) par le nombre d'yeux du fruit. L'offre carbonée correspond à la production d'assimilats par la plante, dont la croissance est stoppée à l'induction florale. Le poids du plant à l'induction florale apparait donc comme une variable d'état clé du système, puisqu'il est d'une part corrélé au nombre d'yeux du fruit, composante essentielle du rendement, et d'autre part déterminant dans l'offre carbonée pour la croissance du fruit. Il était donc important de simuler la croissance végétative de la plante qui a des répercussions non négligeables sur celle du fruit. Ces croissances varient avec les contenus en eau et azote du sol (Combres, 1983; Malezieux, 1988; Py, 1960), simulés au sein des deux modules de bilans hydrique et azoté. Ces deux modules nous fournissent des coefficients de stress qui altèrent la croissance de la plante et du fruit à différents stades du cycle. Ils ont été paramétrés d'après des données issues d'expérimentations en station pendant la thèse. L'effet de différentes doses de fertilisation couplées à deux régimes hydriques différents ont été analysés en pesant tous les mois tous les organes en croissance de l'ananas. Ces mesures, absentes des expérimentations plus anciennes, ont permis de calibrer l'effet des processus de stress, élément indispensable pour décrire la croissance de l'ananas dans des situations climatiques et culturales contrastées. Les sorties du modèle comme le poids du plant, le poids du fruit et la durée du cycle sont correctement simulés par le modèle, quelques soit les conditions climatiques et les pratiques culturales testées.

Dans le but d'utiliser le modèle comme outil d'aide à la conception, il était important d'évaluer sa validité dans des conditions contrastées, mais aussi de vérifier que son niveau de complexité n'était pas redondant et bien approprié au niveau de prévision en fonction des objectifs poursuivis; tous les niveaux de détails ne sont pas forcément nécessaires (Adam *et al.*, 2012; Colbach *et al.*, 2010). De nombreux modèles mécanistes, très détaillés, sont souvent sur-paramétrés, ce qui augmente l'incertitude de prédiction des modèles surtout dans des gammes de variables d'entrées très contrastées. La complexité des modèles n'est pas synonyme de pertinence (Boote *et al.*, 1996; Passioura, 1996; Sinclair and Seligman, 1996). A l'inverse, la simplicité, qui permet une plus grande transparence des formalismes, peut induire une prise en compte des interactions plus restreinte entre les éléments du système. Nous avons donc développé une approche originale, basée sur divers travaux de réduction de modèle (Affholder *et al.*, 2003; Cox *et al.*, 2006; Crout *et al.*, 2014; Crout *et al.*, 2009; Kimmins *et al.*, 2008) afin d'évaluer la structure du modèle et de sélectionner le niveau de complexité le plus approprié en fonction de son utilisation. La suppression des processus de stress du modèle conduit à de larges erreurs de simulation du poids de fruit par rapport au modèle le plus complexe. Les processus inclus dans SIMPIÑA semblent donc nécessaire au bon fonctionnement du modèle pour simuler le rendement de la plante dans la gamme de conditions testées.

1.1.2 L'élaboration de la qualité au cours de la croissance du fruit

L'élaboration de la qualité au cours de ce travail a été envisagée selon deux approches :

- une approche écophysiologique pour la simulation de l'élaboration du contenu en sucres,

- une approche statistique pour la simulation la teneur en acides à la récolte.

Le modèle sucre est basé sur le modèle SUGAR développé sur la pêche par Genard and Souty (1996), révisé par Grechi *et al.* (2008), et nécessite peu de paramètres d'entrées. Les variables d'état du système, poids sec et frais du fruit en croissance, sont simulées par le modèle SIMPIÑA et utilisées comme variables d'entrées du modèle sucre. Les effets du climat et des pratiques sont donc pris en compte via la croissance du fruit simulée. La teneur en sucres à la récolte est bien simulée par le modèle, on obtient un coefficient de détermination R^2 = 0,55 entre les valeurs observées et simulées. Outre le fait de décrire l'accumulation des sucres au cours de la croissance du fruit, cette étude nous a permis d'analyser la variabilité de la teneur en sucres en fonction du statut hydrique de la plante et de la fertilisation reçue. Les teneurs en sucres les plus élevées ont été obtenues dans des régions sèches avec une fertilisation azotée considérée comme non limitante pour la plante. Plusieurs études ont déjà montré qu'un déficit hydrique augmente la teneur en sucres des fruits comme chez la pêche (Lopez *et al.*, 2010), la prune (Intrigliolo and Castel, 2010), et la fraise (Herrington *et al.*, 2009). Une concentration en sucres élevée pourrait s'expliquer par une faible dilution des composés associée à une accumulation active de solutés pour aider le fruit à lutter contre le stress hydrique (Garcia-Tejero *et al.*, 2010; Yakushiji and Morinaga, 1998). Les fruits contenant le moins de sucres ont été cultivés avec une fertilisation assez faible ou nulle (0-150 kg N·ha $^{-1}$) et montrent, par conséquent, des poids plus faibles que les fruits cultivés avec des doses d'azote supérieures. Un déficit azoté peut créer des changements dans la plante, comme une perte foliaire suivie d'une rapide sénescence chez la vigne (Okwuowulu, 1995), moins de composés sont donc accumulés dans des fruits avec une croissance ralentie. De plus, lorsque la plante ne souffre pas d'un manque d'eau, la concentration en solutés est alors diminuée par le processus de dilution qui opère durant la croissance du fruit (Omotoso and Akinridae, 2013).

La méthode utilisée pour déterminer l'acidité du fruit à la récolte n'est pas basée sur la description de processus écophysiologiques comme dans le modèle sucre, les modèles écophysiologique permettant de simuler l'acidité sont généralement très complexes et nécessitent un grand nombre de paramètres (Lobit *et al.*, 2002). De plus, la description du métabolisme crassulacéen de l'ananas impliquant une synthèse de l'acide malique spécifique, la paramétrisation du modèle aurait nécessité de nombreuses mesures. Nous avons donc choisi de déterminer l'effet des variables climatiques, ainsi que leurs périodes d'action sur l'acidité à la récolte à l'aide d'un modèle statistique. De la même manière, une étude récente sur la vigne été développé dans le but de déterminer les périodes durant lesquelles la formation de l'inflorescence est sensible aux stress hydriques et azotés, et d'en quantifier les effets (Guilpart *et al.*, 2014). Il est important pour ce genre d'études de travailler avec un nombre de données importantes, pour vérifier le domaine de validité du modèle retenu et pour éviter sa sur-paramétrisation. L'effet du rayonnement global dans les dernières semaines de croissance de l'ananas, confirmé dans notre analyse, avait déjà été démontré dans plusieurs études (Combres, 1983; Malezieux, 1988; Malezieux and Lacoeuilhe, 1991). La méthode développée dans cette étude a permis de préciser l'effet des autres variables climatiques comme la pluviométrie et la température au cours de la croissance du fruit sur la prédiction de l'acidité du fruit à la récolte. L'effet significatif de ces variables en début de croissance du fruit souligne le fait que la période d'établissement des cellules qui constitueront le fruit joue un grand rôle dans l'accumulation des composés impliqués dans l'acidité de l'ananas.

Les 2 modules de qualité, liés au module plante, constituent un modèle capable de prédire l'effet des pratiques (date de plantation, date d'induction florale, irrigation, et fertilisation), dans une large gamme de conditions climatiques, sur la croissance et la teneur en sucres et en acides des fruits à la récolte. Cet outil permet donc de simuler les décisions techniques prises par les agriculteurs et de fournir des variables simples à évaluer afin d'optimiser les performances des systèmes simulées dans la plupart des zones de production de l'ananas à la Réunion.

1.2. SIMPIÑA , un outil pour l'exploration des scénarios

1.2.1 Une évaluation multicritère des performances des systèmes requise

Les nouveaux enjeux liés au développement d'une agriculture durable incitent à concevoir des systèmes de culture à hautes performances agronomiques et environnementales, tout en produisant des fruits de très bonne qualité pour satisfaire les consommateurs. L'analyse multicritère des systèmes est donc devenue indispensable pour trier et sélectionner des systèmes et faciliter le transfert des innovations (Lançon *et al.*, 2007). La plupart des approches utilisées dans la conception ne prennent pas en compte les différents contextes des exploitations (Sterk *et al.*, 2007), qui pourtant joue un rôle important dans les performances des systèmes. L'utilisation d'approches se basant sur la construction d'une typologie permet de caractériser des groupes d'exploitations en fonction de diverses variables et ainsi d'en comprendre les possibles développements. Cette méthode peut être couplée à des modèles de différentes natures pour participer à la conception de systèmes. L'étude de Meylan *et al.* (2013) font appel à une typologie des pratiques pour adapter un modèle conceptuel utilisé pour la conception de systèmes agroforestiers à base de caféiers au Costa Rica. (Colbach *et al.*, 2006) développent une typologie des rotations de cultures afin d'évaluer l'effet des divers systèmes concernant le risque malherbologique à l'aide du modèle ALOMYSIS qui décrit la croissance et le développement du vulpin. Dans cette étude, nous avons choisi d'élaborer une typologie des pratiques culturales afin de proposer des systèmes de culture innovants, en optimisant les performances des systèmes tout en prenant en compte les principales contraintes des exploitations. L'évaluation multicritère des systèmes ainsi évalués facilite le choix des systèmes les plus appropriés.

Dans le cas de la production d'ananas à la Réunion, l'évaluation multicritère doit se focaliser autant sur les performances agronomiques que les impacts environnementaux, tout en assurant des fruits de qualité. Le modèle développé dans cette étude nous permet d'obtenir des variables à la fois sur le rendement (calibre, volume), l'impact environnemental (pertes en azote), la qualité des fruits (teneur en sucres et en acides à la récolte) et le chiffre d'affaire du producteur, critères nécessaires pour notre cas d'étude.

1.2.2 Vers des systèmes adaptés aux contraintes fonctionnelles et structurales des exploitations

L'exploration des combinaisons de pratiques par le modèle détermine des gammes de pratiques différentes en fonction des types simulés. La contrainte temporelle, rencontrée par le groupe « canniers situés dans des régions humides » est prise en compte par une adaptation des dates de plantation et d'induction florale, pour favoriser la période de croissance végétative hors période de campagne sucrière. En effet, c'est durant le stade plantation – induction florale qu'interviennent les interventions techniques (sauf récolte) sur la parcelle. La date d'induction de ce type de système semble donc pouvoir être avancée dans le temps par rapport aux systèmes actuels. Il en va de même pour le groupe « monoculteurs traditionnels des hauts » malgré une stratégie de gestion du cycle différente. Ces exploitations situées à des altitudes assez hautes, avec des températures fraîches, et ne bénéficiant pas de systèmes d'irrigation ont des cycles de production dépassant les 18 mois pour atteindre un poids de fruit acceptable. On peut donc faire l'hypothèse qu'avancer la date d'induction florale résulterait d'un plus faible rendement. Néanmoins, les périodes de plantation actuelles qui se situent entre les mois d'Avril et Septembre, semblent pouvoir s'étendre toute l'année dans les systèmes sélectionnés. Ceci implique donc des récoltes toute l'année, contrairement aux systèmes actuels qui permettent un regroupement des récoltes aux périodes de fêtes (Noël et Pâques). Cette nouvelle gestion du cycle implique une commercialisation des fruits différente, les fruits ne seraient plus destinés à l'export, qui représente la rentrée d'argent la plus importante en termes de prix/kg, mais au marché local pouvant accepter des fruits de faibles calibres. Cependant, des phénomènes de floraisons naturelles peuvent opérer en cas de raccourcissement de la photopériode et de vernalisation due aux basses températures nocturnes (Bernier, 1988). Dans le futur, il serait sans doute pertinent d'inclure un module de prévisions de floraisons naturelles pour simuler des systèmes ayant des conditions climatiques favorisant ces phénomènes, puisque ces processus interfèrent grandement dans le développement et l'élaboration de la qualité du fruit. Une analyse de l'effet de la variabilité climatique interannuelle sur les performances du système pourrait compléter cette étude afin de simuler le risque d'occurrence des floraisons naturelles dans une région donnée.

Le module économique construit n'est pas fixe et peu voir ses paramètres changer avec l'évolution des prix et des subventions attribués en fonction des marchés ciblés. Les systèmes doivent pouvoir être évalués en fonction de l'évolution des différents contextes (économiques, climatiques). Tous les systèmes sélectionnés démontrent une diminution de l'utilisation de la fertilisation azotée pour atteindre une haute performance environnementale calculée d'après un coefficient estimant les pertes en azote par lessivage. Seul le groupe « intensifs diversifiés des bas » semble pouvoir atteindre des doses d'azote à 300 kg ha^{-1}, la moyenne actuelle de ces systèmes excédant 350 kg ha^{-1}. Ceci étant possible car les zones de production situées dans des zones sèches irrigables sont pour la plupart en irrigation au goutte à gouttes, limitant les pertes d'azote par lessivage.

1.2.3 Les limites des indicateurs de performances

Le lessivage de l'azote a été choisi comme critère d'évaluation de l'impact environnemental. Pour le moment, ce critère nous permet seulement de comparer les systèmes entre eux, mais ne nous fournit pas une estimation précise de la quantité d'azote lessivée, ce module n'ayant pas été validé avec des observations sur le terrain. Il serait intéressant d'affiner cette valeur afin d'optimiser les quantités d'azote apportées en quantifiant précisément les pertes (mesures lysimétriques par exemple). Dans l'objectif d'étendre la démarche à des zones où l'utilisation de produits phytosanitaire est importante, l'évaluation des systèmes simulés pourrait être complétée par des indicateurs évaluant le risque de pollution des eaux de surface et de profondeur par les produits phytosanitaires, e.g. indicateur Rpest (Tixier *et al.*, 2008)

Une autre voie d'amélioration de la démarche serait la prise en compte de nouvelles pratiques culturales, comme par exemple l'apport de fertilisation organique à la plantation après une mise en jachère de la parcelle. Cette pratique, actuellement non implémentée dans le modèles SIMPIÑA, pourrait participer à réduire considérablement la fertilisation chimique, voire la remplacer. Il serait nécessaire d'inclure un module capable de décrire la dynamique des teneurs en éléments fertilisants de différents engrais organiques (végétales ou animales) dans les sols réunionnais pour comprendre les périodes de minéralisation des produits et les effets sur l'absorption de la culture. Des travaux sur l'emploi des jachères en culture d'ananas et sur la minéralisation de la matière organique de différents produits résiduels organiques (d'origine urbaine, agro-industrielle ou agricole) ont été développés, respectivement, en Martinique et à la Réunion) (Rothé *et al.*, 2014) Un module de bilan azoté intégrant ces pratiques devrait pouvoir être développé et paramétré prochainement.

Pour le moment, le modèle économique ne prend pas en compte les coûts de production associés à la culture de l'ananas. Dans notre étude, les systèmes sélectionnés atteignent de performances économique élevées mais l'intégration d'un module de marge brute fournirait un indicateur plus pertinent pour comparer les systèmes (Nelson *et al.,* 1998). Une des principales difficultés dans le développement d'un module de marge brute est l'estimation des temps de travaux et la main d'œuvre requise pour les opérations technique, et plus particulièrement lorsque l'ananas n'est pas la principale culture de l'exploitation. Il sera important dans le futur d'améliorer le critère d'évaluation économique, surtout si des pratiques culturales nécessitant plus ou moins de main d'œuvre sont intégrées dans la démarche. Les pratiques associant de la main d'œuvre supplémentaire étant souvent favorisées dans la conception de systèmes innovants, comme le démontre l'étude sur la conception de nouveaux systèmes durables agroforestiers au Malawi (Thangata and Alavalapati, 2003).

Le modèle SIMPIÑA est pour le moment paramétré pour la variété la plus commercialisée à la Réunion, le 'Queen Victoria'. Les caractéristiques de croissance diffèrent entre les cultivars, comme le nombre de feuilles, le ou le poids du plant au moment de l'induction florale, comme le démontre (Fournier *et al.*, 2010). Des expérimentations seraient nécessaires pour quantifier les effets de différents niveaux d'alimentation hydrique et azoté pour adapter les paramètres de croissance de la plante et du développement du fruit, mais ne nécessiteraient pas à priori d'ajout de modules supplémentaires, sauf en cas de sensibilité à une maladie ou à un ravageur non présents sur le 'Queen Victoria'.

2. Conclusion

L'utilisation de modèle de culture constitue un moyen très efficace pour faire de la conception en explorant une large gamme de combinaisons techniques. De plus, il est très facile de coupler les modèles, qui nous fournissent des indicateurs difficilement mesurables en champ, avec les méthodes automatisées d'analyse multicritère.

Localement, la construction d'un modèle a*d hoc* permet de simuler correctement les effets des principales contraintes présentes dans les zones étudiées. Le modèle se compose pour le moment de peu de modules, dont la force est d'avoir été validé dans une large gamme de climats et de pratiques. Les élaborations du rendement et de la qualité sont décrites de manière précise à l'aide de processus biophysiques (excepté le module de prédiction de l'acidité qui est statistique) au sein d'un même outil qui intègre la majorité des connaissances sur la plante et ses spécificités. Par son approche modulaire, le modèle est donc capable d'intégrer de nouvelles conduites en cas d'une modification du contexte de production, qui peut évoluer très rapidement, comme l'interdiction de l'utilisation d'une substance fertilisante, ou l'impact de l'utilisation de pesticides sur l'environnement.

Il reste nécessaire d'évaluer le modèle dans son ensemble en l'utilisant de manière interactive avec les agriculteurs. Le modèle permettra à la fois de définir des systèmes de culture mais aussi d'évaluer la capacité du modèle à effectuer des choix pertinents. Afin de concevoir des systèmes optimisant la fertilité des sols des plantations de mais au Zimbabwe, Carberry *et al.* (2013) ont collaboré avec les agriculteurs et les acteurs pour élaborer des prototypes qui démontre que l'ajout d'amendements de mauvaises qualité avait des effets sur le rendement à cause d'une faible immobilisation de l'azote.

Nous avons contribué à répondre dans cette thèse aux organisations de producteurs et aux producteurs d'ananas réunionnais, conformément aux objectifs de cette thèse CIFRE (Conventions industrielles de formation par la recherche).

- les expérimentations mises en place pour la calibration du modèle ont fourni des résultats intéressants sur l'effet du poids de rejet sur la croissance de la plante, ainsi que sur l'effet de différentes doses de fertilisation azoté et d'irrigation,

- le modèle, évalué avec de nombreux jeux de données, permet de simuler des systèmes situés dans la plupart des zones de production de l'ananas sur l'île de manière satisfaisante ;

- le travail d'enquête reflète les pratiques actuelles des producteurs, indispensables afin d'identifier leurs marges de manœuvre pour la conception de systèmes innovants ;

- les performances des systèmes calculées au sein de différents modules de nature différentes nous permettent d'évaluer les systèmes promus de manière multicritère ;

- le modèle constitue un outil intéressant pour discuter avec les acteurs de sa capacité à proposer des choix techniques pertinents et des contraintes pouvant limiter le potentiel d'adaptation des innovations.

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